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Neural signatures of inhibitory control in intra-sentential code-switching: Evidence from fMRI[☆]

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ABSTRACT

In this study we examined the neural control mechanisms that are at play when habitual code-switchers read code-switches embedded in a sentence context. The goal was also to understand if and to what extent the putative control network that is engaged during the comprehension of code-switched sentences is modulated by the linguistic regularity of those switches. Towards that goal, we tested two different types of code switches (switches at the noun-phrase boundary and switches at the verb-phrase boundary) that despite being both represented in naturalistic corpora of code switching, show different distributional properties. Results show that areas involved in general cognitive control (e.g., pre-SMA, anterior cingulate cortex) are recruited when processing code-switched sentences, relative to non-code-switched sentences. Additionally, significant activation in the cerebellum when processing sentences containing code-switches at the noun-phrase boundary suggests that habitual code-switchers might engage a wider control network to adapt inhibitory control processes according to task demands. Results are discussed in the context of the current literature on neural models of bilingual language control.

For bilinguals, producing or comprehending code-switched utterances (i.e., utterances that switch from one language to the other) is seemingly effortless. Yet, code-switching is actually associated with a measurable processing cost, even when bilinguals are highly proficient in both of their languages. The literature has demonstrated that switching between two languages for isolated items results in longer naming compared to non-switch conditions (e.g., Altarriba, Kroll, Sholl, & Rayner, 1996; Meuter & Allport, 1999), and the observed switching costs are greater when switching from the weaker language (L2) into the stronger first language (L1) (Bobb & Wodniecka, 2013; but see Costa & Santesteban, 2004 for highly-proficient bilinguals who show no asymmetric switching cost in single item language switching, and Gullifer, Kroll, & Dussias, 2013 for evidence of a reduced language switching cost when lexical access happens during sentence comprehension). In addition, an emergent body of research on the cognitive correlates of language switching in more naturally occurring situations such as switching within meaningful sentences (i.e., intra-sentential code-switching) have also reported similar switch-related costs within single language sentences (for a recent review see Van Hell, Litcofsky, & Ting, 2015).

These key findings on the effects of bilingual language switching have demonstrated that the bilinguals' two languages are

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constantly activated, and that it is virtually impossible for bilingual speakers to switch them off, even when intending to speak one language alone (e.g., Kroll, Bobb, & Wodniekca, 2006) raising the central question of what are the cognitive and neural mechanisms that enable bilinguals to control their languages. The Inhibitory Control (IC) model (Green, 1998) proposes that bilinguals need to inhibit the more dominant of the two languages for successful language production in the L2 (e.g., Green, 1998; Levy, Mcveigh, Marful, & Anderson, 2007; Linck, Kroll, & Sunderman, 2009; Philipp, Gade, & Koch, 2007). If both languages are activated even when bilinguals intend to speak one language alone (Kroll, Bobb & Wodniekca, 2006), inhibiting the stronger language will allow the weaker language to be spoken, and will facilitate successful production of the intended language. The IC model is supported by neuroimaging research showing that negotiating between two languages engages a number of brain regions that are implicated in domain general cognitive control, including the dorsolateral prefrontal cortex, anterior cingulate cortex (ACC), and basal ganglia, including the left caudate/putamen (Blanco-Elorrieta, Emmorey, & Pylkkänen, 2018;). These findings show that bilinguals utilize language non-specific, domain-general cognitive processes to control, monitor and inhibit the strongest language, and to successfully produce the intended language (Abutalebi & Green, 2007; Abutalebi et al., 2011).

The majority of past studies that have examined models of bilingual language control have capitalized on tasks in which participants have to switch languages from trial to trial, or tasks in which bilinguals are required to switch languages across blocks. Crucially, comparing item by item language switching to blocked language switching has allowed researchers to determine which different neural control mechanisms are at play when a language needs to be controlled more globally (i.e., for a potentially prolonged amount of time, such a whole naming block) relative to more "local" control mechanisms that would need to temporarily inhibit a lexical item while still keeping the other language active and ready for retrieval (i.e., item by item switching tasks). For example, Guo, Lsiu, Misra, & Kroll (2011) used functional magnetic resonance imaging (fMRI) to determine what neural networks support block by block language switching and item by item language mixing. In that study, Chinese-English participants named a block of pictures in Chinese (the L1), and then a block of pictures in English, while another group of participants performed the naming task in the opposite order. In the final block, participants named pictures in either English or Chinese depending on a frame color cue, thus probing local control. Results showed that during the blocked naming paradigm, dorsolateral prefrontal cortex and parietal cortex were more activated, consistent with these regions supporting global language control, while the dorsal ACC and the supplementary motor area (SMA) were important during item by item inhibition suggesting different networks are responsible for global versus local language inhibition.

Studies such Guo et al., (2011) relied on single lexical items that were repeated across blocks. As such, the results of that study were limited to the items that were previously named, and no answer was provided as to whether the same network would be engaged when controlling the strongest language more globally, i.e., even for items that were not previously activated. Two more recent fMRI studies have tackled this question, revealing that the recruitment of the bilingual control network emerges and tunes itself beyond local control, and that is also shaped by proficiency. For example, Blanco-Elorrieta et al. (2018) reported that the dorsal portion of the ACC (dACC) and the presupplementary motor area (pre-SMA) were activated when bilinguals had to name the previously named items, while dorsolateral prefrontal cortex, inferior parietal areas, and the caudate where recruited when naming items that were not previously named. Rossi et al.'s results (2018) extend Branzi et al.'s by showing that when naming the identical items in the L1 after having spoken the L2, bilinguals showed greater activation than monolinguals in right precentral gyrus, and central cingulate gyrus. The results also demonstrate a graded engagement of the control network, with greater activation for bilinguals than monolingual controls when naming new items which were not previously named, but which were semantically related to previously named items, in bilateral middle cingulate gyri, and left precuneus. These results suggested that control processes go beyond the specific item and expand to the broader semantic category. Critically, Rossi et al.'s results show that bilinguals activated a wide control network even for completely novel items, engaging bilateral caudate, putamen, anterior cingulate, and anterior temporal lobe. Collectively, these studies provide crucial data showing that the bilingual control network is more malleable than previously thought, and that it engages differentially depending on the level of control that needs to be exercised, whether it be more local or global.

The body of literature on the neural substrates of bilingual language switching is summarized in a recent metanalysis of fMRI studies of language switching (Luk et al., 2012) that identifies eight brain regions with significant and reliable activation, mainly: left inferior frontal gyrus, left middle temporal gyrus, left middle frontal gyrus, right precentral gyrus, right superior temporal gyrus, midline pre-SMA and bilateral caudate nuclei. However, most of the extant neural evidence is still primarily limited in that it is based on single items and provide limited insight into how the control network functions during more naturalistic language processing, such as in sentences. Only a few fMRI studies have investigated the neural correlates of language switching beyond the single word level (for ERP evidence on intrasentential code-switching, see e.g., Beatty-Martínez & Dussias, 2017; ; Mainy et al., 2008; Rubia, Smith, Brammer, & Taylor, 2003. Only a couple of fMRI studies provide data on sentential code-switching. In one study, Abutalebi et al. (2007) studied how the bilingual control network engages when proficient Italian-French bilinguals heard longer passages that switched from Italian (the L1 but not the language of immersion, thus the less exposed language) into L2 French (which was however the current language of immersion for these speakers) and vice-versa. In that study, in addition to switching between languages, the switches were also manipulated to be "regular" switches that respected the constituents of the sentence structure, or "irregular" switches that violated the constituency of the sentence structure. The results showed that when regular switches happened from the L2 into the L1 (Italian) there was selective activation of the left caudate, the anterior and posterior cingulate cortex, and the right supermarginal gyrus which are all neural areas that have been involved in cognitive and executive control. Instead, the reversed comparison, i.e., regular switches from the L1 into the L2 French (the language of immersion) activated the superior parietal lobule, the left superior temporal pole, and the right temporal pole, suggesting greater reliance on language regions. Crucially, there was a dissociation between grammatically correct switches and irregular switches with regular switches showing a pattern of brain activity typical of lexical processing, whereas irregular switches engaged brain structures involved in syntactic and phonological aspects of language processing. In another notable recent study, Blanco-Elorrieta and Pylkkänen (2017) examined the comprehension of language switches occurring in naturalistic speech during which bilinguals listened to clips of real conversations between Arabic-English bilinguals that included switches from Arabic to English and switches from English to Arabic, as well as single-language control clips. The results showed that processing switches in a natural speech context elicited an activity increase in the right auditory cortex (which was not sensitive to the direction of the switch), but no switching effects were observed in the dorsolateral prefrontal cortex and the ACC, as observed in other paradigms that rely on less naturalistic switching paradigms. Taken together, these two studies (Abutalebi et al., 2007; Blanco-Elorrieta & Pylkkänen, 2017) suggest that the control network engaged in the comprehension of code-switches in more naturalistic paradigms, could be fundamentally different than for bilinguals who are however non-habitual code-switchers and for more artificial switching paradigms. In addition, even though in was not clear in these two studies whether the recruited speakers engaged in habitual daily code-switching, they do open the question as to whether "habitual code-switching" i.e., fluently switching between two languages within a single sentence in every-day life interactional contexts (Deuchar, 2012) shapes the recruitment of the control network.

The growing recognition that bilingual language control is heavily dependent on variable interactional contexts has led to the proposal that the neural circuits that subserve bilingual control capacities (e.g., goal maintenance, conflict monitoring, interference suppression, selective response inhibition) will be engaged adaptively depending on the interactional context as proposed by the adaptive control hypothesis (Green & Abutalebi, 2013). The model proposes that the cognitive and neural network is shaped in three different interactional contexts, mainly single language context (i.e., the two languages are kept separate), dual language context (i.e., the speaker might switch between languages in the course of a conversation, but not necessarily switch within a sentence) and a dense code-switching (i.e., when bilinguals switch languages fluidly within the same sentence). The Adaptive Control Hypothesis proposes that the network changes and adapts its engagement in speakers from a dense-code switching environment involving adaptation in right cerebellar and left inferior frontal regions connectivity necessary to mediate late retrieval and activation of both languages at the same time, while for speakers who are in a dual-language context adaptation is predicted in the circuit encompassing frontal cortical regions, important for conflict monitoring and interference suppression. Moreover, the model assumes top-down effects on the engagement of the neural control network interacting with task demands predicting that individuals who are used to a dense code-switching mode will engage the network differentially when faced with a global versus local language switching task relative to individuals who keep the use of their two languages more separate, such as in a single language context, or speakers who engage mostly in a dual-language context.

Frequent code-switching within a sentence, as is common in, for example, the Spanish-English speaking Hispanic community in the US (denoted as habitual code-switchers), represents a prime example of what Green and Abutalebi's dense code-switching interactional context. Despite its prevalence in actual bilingual conversation, and despite the voluminous literature on the syntactic and social constraints that regulate code-switching, relatively little is known about the neural mechanisms that regulate this phenomenon. In other words, little is still known about which neural areas are engaged while bilinguals code-switch between their two languages beyond the single word level. This is especially important because for many bilinguals code-switching is an integral part of their communicative behavior.

The goal of this study is to investigate the neural underpinning of language control during sentential code-switching comprehension in habitual code-switchers. We examined whether habitual code-switchers are sensitive to regularities in code-switched sentences and whether the neural control network is shaped by the linguistic regularities of those code-switches. Spanish-English habitual code-switchers processed sentences with embedded code-switches during an event-related fMRI paradigm. Participants read sentences in Spanish or English only (without code-switches) and sentences that began in Spanish and switched into English midstream (40 sentences per condition), mirroring code-switching patterns found in naturalistic corpora (e.g. Deuchar et al., 2012). The goal was also to investigate whether the network that was engaged during the comprehension of code-switching was modulated by code-switching linguistic regularities, by including two types of switches that occur in natural language switching environments: switches that occur at the noun phrase (e.g. El crítico pensó que *the novel* would take several days to read) or at the verb phrase (e.g. El crítico pensó que la novela *would* take several days to read). Importantly, although both types of code-switches are found in naturalistic corpora, code-switches at the left noun phrase boundary are less frequent than switches at the verb phrase boundary (Deuchar et al., 2012). This asymmetry allows us to as the question of as to whether the observed control network will engage differentially between the two types of switches.

1. Methods

1.1. Participants

Twenty-three, right-handed, Spanish-English bilingual, healthy young adults participated in the study. Four participants were excluded from the fMRI analysis for excessive motion artifacts. As such, data from 19 participants (mean age 25.3; age range 19–35; 10 male) will be reported. All participants had normal or corrected to normal vision, and none had a history of neurological or psychological disorders. Each participant provided informed consent and was paid for their participation. All experimental procedures were approved by the Institutional Review Board of the Pennsylvania State University. All participants were recruited to be Spanish-English bilinguals who code-switched on a regular daily basis. They all completed a language history questionnaire (LHQ) in which they rated their language proficiency in English and Spanish, for speaking, writing reading and oral comprehension. Importantly, the LHQ contained a special section composed of seven questions on code-switching behavior, including questions such as: "Code-switching means using more than one of your languages in the same sentence when you are talking to someone else. Do you ever code-switch?". A copy of the LHQ used is provided in Appendix A. According to the self-reported measures, all participants reported code-switching on a regular basis (reporting “Most of the times”), both in oral and written contexts. Participants provided also self-reported measured of proficiency in Spanish and English: English speaking proficiency (mean = 8.6); English oral comprehension (mean = 9.2); English reading comprehension (mean = 9); English writing (mean = 8.7); Spanish speaking proficiency (mean = 9.5); Spanish oral comprehension (mean = 9.7); Spanish reading comprehension (mean = 9.2); English writing (mean = 8.9).

1.2. Experimental material

Experimental material consisted of four conditions: English only sentences, Spanish only sentences, Spanish sentences that switched into English at the noun phrase boundary, and Spanish sentences that switched to English at the verb phrase boundary. Sentences were created by native Spanish-English bilinguals, and taken from previously published materials from our group (Dussias & Cramer Scaltz, 2008). All the stimuli followed corpora of Spanish-English code switching reflecting the naturalistic distribution of code-switches showing that the directionality of the sentential code-switches is mostly from Spanish into English (Poplack, 1980, 2015). As such, for the purposes of the present design, we followed naturalist pattern of code-switching, including code-switched sentences that started in English and switched into Spanish. Sentences that began in English and switched into Spanish were not included, because these types of switches are less common among bilingual speakers (Poplack, 1980, 2015).

Code-switched items were represented by two types of code switches: 1) sentences that started in Spanish and switched into English at an embedded subject noun phrase (less frequent), e.g., “El crítico pensó que *the novel would take several days to read*” (“The critic thought that the novel would take several days to read”) and code-switches at the verb phrase boundary (more frequent), e.g., “El crítico pensó que la novela *would take several days to read*”.

Experimental items were constructed in quartets, with one version of the sentence for each condition type (English, Spanish, Noun Switch, Verb Switch). Equal numbers of sentences for each condition (N = 40) were distributed randomly across four experimental lists, and lists were counterbalanced across participants such that each participant only saw one version of each sentence context. Across all conditions, sentences were matched for length and sentence structure. Additionally, to minimize the possibility of word-word priming, all sentences were screened to ensure that there were no associated words within the sentences. Example sentences are presented in Table 1, and a full list of the materials is reported in Appendix B.

1.3. Experimental fMRI task procedure

Each trial consisted of a single sentence (duration = 4s) presented in its entirety in the center of the screen. Sentences were presented in black font (type = courier new, size = 22) on a white background. Participants were asked to read each sentence and try to understand it. Yes-no comprehension questions (duration = 2 s) followed 25% of the sentences to ensure that participants were attentive to the stimuli during the fMRI session. When comprehension questions were presented, there was a 500 ms inter-stimulus-interval between the sentence and question. Comprehension questions were equally distributed across conditions and to avoid a response bias there was an equal number of questions intended to elicit ’yes’ and ‘no’ responses. Because memory may be influenced by the language in which the information was initially encoded, the language in which the questions was presented was always consistent with the language in which the information was initially presented. This resulted in roughly equivalent number of English and Spanish questions. Participants were provided with 8 novel practice sentences to familiarize them with the experimental procedure.

Each sentence (or sentence and question pair) was followed by a variable inter-trial-interval 4–10s in length (average interval 6.2s). Trial order across conditions and inter-trial-interval were randomized to minimize participant preparation and anticipation of stimuli. Each run began and ended with the presentation of a fixation cross (duration = 15s), and a fixation cross was presented between each sentence pair. Sentences (40 per condition) were presented across 6, 5-min runs. All stimuli were presented using the Brain Logics MRI Digital Projection System, and experimental parameters were controlled via E-prime (Psychology Software Tools, Pittsburgh, PA; www.pstnet.com). Responses were recorded with a hand-held fiber optic response box (Current Designs, Philadelphia, PA, USA).

1.4. Acquisition of MRI data

MRI scanning was completed on a Siemens 3.0 T 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 commisures 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 fSPGR pulse sequence (TR = 1400 ms;

Table 1
***Examples of experimental stimuli*.**

Condition	Example Sentences
English	The critic thought that the novel would take several days to read.
Spanish	El crítico pensó que la novela llevaría varios días para leerla.
Noun-Phrase boundary CS	El crítico pensó que *the novel would take several days to read*.
Verb-Phrase boundary CS	El crítico pensó que la novela *would take several days to read*.

*Sentence content was not repeated within participants; Each participant saw only one sentence from each quartet.

TE = 2.01 ms; TI = 900 ms; FOV = 256 × 256 mm; flip angle = 9°; voxel size = 1 × 1 × 1 mm; 160 contiguous slices). Functional images sensitive to blood oxygen level-dependent (BOLD) contrast were acquired using an EPI pulse sequence (TR = 2s; TE = 25 ms; FOV = 240 mm; flip angle = 70°; voxel size = 3.8 × 3.8 × 3.8 mm; 34 contiguous axial slices). Each of 5 runs consisted of the acquisition of a time series of 158 brain volumes and a sixth run consisted of 175 brain volumes (~5 min runs). Two initial RF excitations were performed to achieve steady state equilibrium and were subsequently discarded.

1.5. fMRI data analysis

Preprocessing and first level analysis of each individual run for each participant were performed using SPM 12 (Wellcome Department of ImagingNeuroscience, London, UK). Functional image data were motion-corrected, high-pass filtered, and spatially smoothed using a Gaussian kernel (FWHM = 8 mm). No participant had a greater than 4 mm movement in the X, Y, or Z dimension, and motion parameters were included in the overall SPM12 model. Functional images of each participant were co-registered to structural images in native space, and structural images were normalized to the Montreal Neurological Institute (MNI) 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. A double γ function was used to model the hemodynamic response for each trial in each run. The first-level analysis included standard trials and resting trials as separate regressors, and motion parameters as nuisance variables. Four conditions including Spanish only sentences, English only sentences, noun-switched and verb switches, and onsets and durations corresponded to the start and the duration of the stimulus. Duration was set at 4 s in the model. The modeled data from each participant and run were combined and a second level analysis was performed.

These second level analyses were then combined across participants into a group level analysis to identify voxels that were activated by each sentence type. Additionally, a repeated measures ANOVA was calculated to assess for main effects of language and code-switching. All whole-brain analyses were considered statistically significant at a voxel-level *p*-value < .001 (not corrected for multiple comparisons), and a cluster level *p*-value < .05 family-wise corrected for multiple comparisons (FWE correction; Friston, Holmes, Poline, Price, & Frith, 1996; Hayasaka, Phan, Liberzon, Worsley, & Nichols, 2004; Worsley et al., 1996). This restricted to a maximum of 0.05 the probability of falsely finding a cluster with a size equal or superior to the critical threshold. Coordinates of the centroids 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.

In addition to the analyses described above, the single trial peri-event averages for each trial and segment were measured at each voxel (Gadde & McCarthy, 2009). Percent signal change was determined by averaging the hemodynamic response elicited by each condition and calculating the difference between baseline and peak points for each condition. These t-statistic peri-event waveforms were combined across participants using a random effects analysis.

Table 2

Functional activation results contrasting switches to non-switches and non-switches to switches.

SWITCHES > NON-SWITCHES	Brodmann area label	Hemisphere	Cluster size	z value	COORDINATES		
					x	y	z
Supplementary Motor Area	BA 6	Right	1033	5.25	4	6	56
Supplementary Motor Area	BA 6	Left		4.43	−6	0	52
Mid Cingulum	BA 24	Left		4.23	−4	−2	40
Inferior frontal gyrus, triangular portion	BA 45	Left	1429	4.84	−44	18	22
Precentral gyrus	BA 8	Left		4.44	−44	14	32
Rolandic operculum	BA 6	Left		4.01	−54	2	12
Inferior parietal, supramarginal and angular gyri	BA 39	Left	1072	4.63	−30	−54	42
Superior parietal gyrus	BA 7	Left		4.42	−24	−80	48
Inferior parietal, supramarginal and angular gyri	BA 7	Left		4.29	−28	−64	44
Caudate Nucleus		Right	770	4.61	20	10	16
Caudate Nucleus		Right		4.07	22	−16	18
Caudate Nucleus		Right		3.85	24	−8	18
Superior parietal gyrus)	BA 7	Right	1612	4.41	26	−72	50
Inferior parietal, supramarginal and angular gyri	BA 40	Right		4.4	44	−48	46
Precuneus	BA 7	Right		4.05	16	−74	44
Fusiform gyrus		Left	706	4.39	−46	−64	−18
Inferior occipital gyrus	BA 19	Left		4.34	−50	−74	−6
Cerebellum	BA 19	Left		4.02	−24	−62	−32
Inferior frontal gyrus, triangular part	BA 45	Right	812	3.89	36	28	14
Precentral gyrus	BA 6	Right		3.88	52	−8	42
Precentral gyrus	BA 6	Right		3.84	56	10	38
Middle temporal gyrus	BA 21	Left	345	3.81	−58	−48	2
Middle temporal gyrus	BA 21	Left		3.67	−64	−46	−6
Middle temporal gyrus	BA 22	Left		3.62	−64	−46	12
NON-SWITCHES > SWITCHES	No significant clusters						

2. Results

2.1. fMRI activation results

Two critical analyses were performed to reveal the neural network that is implicated in sentential code-switching as a whole, and more specifically to reveal if the implicated network is modulated by the type of sentential code-switch. Additional analyses of interest, such as contrasting English to Spanish only sentences, and activations for English greater than rest (baseline), and Spanish greater than rest are provided in Appendix C.

1) *Main effect of switching (all switches greater than all non-switches)*: In this contrast activation for all the switched items, independent of the switch condition were compared to all non-switched items (i.e., Spanish and English only sentences). First, switched items elicited significantly greater activation than non-switched items in a number of clusters including right midline pre-supplementary motor area, and the mid portion of the anterior cingulate cortex (ACC) which have been previously found to be implicated in bilingual language control and in language production more generally). In addition, a significant cluster of activation was found in the triangular portion of the left inferior frontal gyrus with subclusters of activation in the superior frontal sulcus, which have also been found to be active during bilingual language control and simultaneous interpreting. Another significant cluster of activation was found in left angular gyrus with significant subclusters in left dorsolateral prefrontal cortex that are areas found active while inhibiting irrelevant semantic information (Lewis, Poeppel, & Murphy, 2019) and during language switching (Blanco-Elorrieta & Pylkkänen, 2017). In addition, a significant cluster of activation was found in right caudate which has been previously reported to be involved in bilingual language switching (Luk, Green, Abutalebi, & Grady, 2011), and during a bilingual visual recognition task (Peeters, Vanlangendonck, Rueschemeyer, & Dijkstra, 2019). The analysis also revealed a significant cluster of activation in the right parietal lobe with significant subclusters in right posterior parietal lobe, an area part of the attentional network (Rubia, Smith, Brammer, & Taylor, 2003), and found during conflict monitoring and resolution during non-linguistic control tasks (Abutalebi et al., 2012). The analysis also revealed that left fusiform, and left middle occipital visual cortex were also activated. Finally, the analysis revealed the activation of the right triangular portion of the inferior frontal gyrus, and left middle temporal gyrus which are typical language comprehension areas in the temporal lobe. The results of this contrast are shown in Table 2 and in Fig. 1.

Crucially, the opposite contrast i.e., non-switches greater than switches was also performed, but the analysis yielded no significant results.

3. Discussion and conclusions

The goal of this study was to examine the neural control mechanisms that are at play when habitual code-switchers process intra-sentential code-switches. Past behavioral and neural models of bilingual language control have posited the existence of potent cognitive and neural mechanisms that enable bilinguals to efficiently monitor and control their languages during speech processing (Green, 1998). In particular, Abutalebi and Green's model of bilingual language control (Abutalebi & Green, 2007) postulates an extensive network that includes dorsolateral prefrontal cortex, ACC, and subcortical structures such as basal ganglia, left caudate/-putamen that is crucial to enable bilingual speakers to successfully produce and exert control during bilingual language processing (Abutalebi et al., 2011). This model has been further extended to include the idea that bilingual language control is highly adaptive (Green & Abutalebi, 2013), and engages differentially depending on diverse interactional demands, such as in dense-code switching contexts where right cerebellar activity and the left inferior frontal regions seem to be necessary to mediate late retrieval and activation of both languages at the same time.

However, the majority of fMRI studies so far have tested those theories primarily utilizing single word switching experimental paradigms. Fewer studies have tested these models during more naturalistic sentence-level switching tasks (but see Blanco-Elorrieta & Pylkkänen, 2017 and Abutalebi et al., 2007), and even fewer have investigated these processes in speakers who report to be habitual code-switchers. Here, even though we did not directly compare single word switches with sentential switches, we explored these models by investigating the neural substrates of sentential code-switching, specifically in habitual code-switchers, and ask if and to what extent cognitive experience with the statistical regularities of different code-switches shape what control regions are engaged during the comprehension of different types of sentential code-switches.

Table 3
Functional activation results contrasting switches at the noun phrase boundary to switches and the verb phrase boundary, and the opposite contrast, i.e., switches at the verb phrase boundary to switches at the noun phrase boundary.

SWITCHES AT NOUN BOUNDARY > SWITCHES AT VERB BOUNDARY	Brodmann area label	Hemisphere	Cluster size	z value	COORDINATES		
					x	y	z
Fusiform gyrus	BA 19	Left	6874	4.90	−12	−66	−2
Calcarine fissure	BA 23	Right		4.84	15	−54	8
Superior occipital gyrus	BA 19	Left		4.80	−20	−78	24
SWITCHES AT VERB BOUNDARY> SWITCHES AT NOUN BOUNDARY	No significant clusters						

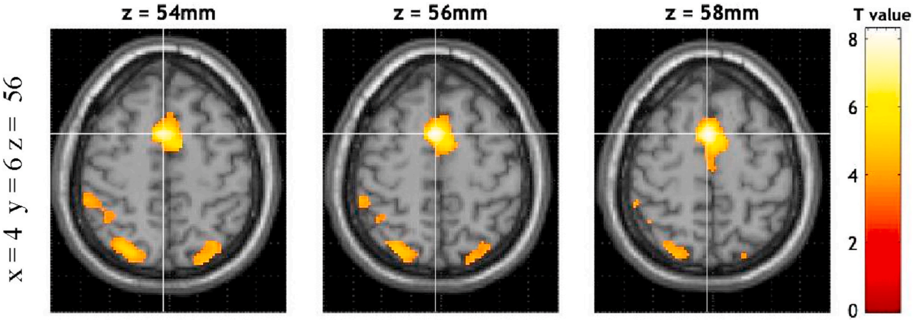

Fig. 1. Functional activation for switches greater than non-switches.

2) *Main effect of switch type: switches at the noun boundary greater than switches at the verb boundary:* This contrast examined the direct comparison of less frequent switches at the noun phrase boundary (i.e., "*El crítico pensó que la novela would take several days to read*") to more frequent switches at the verb phrase boundary, (i.e., "*El crítico pensó que la novela would take several days to read*"). The results revealed that switches at the noun boundary relative to switches at the verb-phrase boundary elicited a significant activation in the left fusiform gyrus. The analysis also revealed a significant activation in the right calcarine fissure which is implicated in complex visual processing. In addition, an activation in the left occipital gyrus was observed. The results of this contrast are shown in Table 3 and in Fig. 2. Critically, there were no regions in which switches at the verb boundary elicited greater activation than switches at the noun boundary.

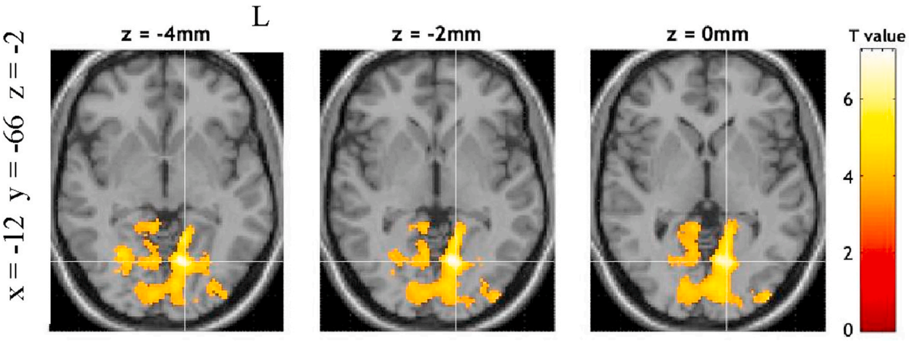

Fig. 2. Functional activation for switches at the noun phrase boundary greater than switches at the verb phrase boundary.

Overall, our data support previous studies showing that processing of sentential code-switches engages a neural network encompassing cortical and subcortical areas, such as pre-supplementary motor area, anterior and mid cingulate cortex, caudate, and cerebellum. Pre-supplementary motor area, and left mid ACC have been extensively reported to be engaged in bilingual language control (Luk et al., 2012; Rossi, Newman, Kroll, & Diaz, 2018), as part of the original bilingual control network (Abutalebi & Green, 2007; Abutalebi et al., 2011). Pre-SMA and ACC have been also found active during sentence level shadowing task in interpreters (Hervais-Adelman, Moser-Mercer, Michel, & Golestani, 2014), and have been found active in the comprehension of language switching (Blanco-Elorrieta & Pylkkänen, 2016) suggesting an overall role of pre-SMA and ACC during bilingual language control in sentential contexts. However, ACC and pre-SMA have not been observed in more naturalistic language-switching. for example, Blanco-Elorrieta and Pylkkänen (2017) examined the comprehension of language switches occurring in naturalistic speech in Arabic-English bilinguals and showed that processing switches in a natural speech context elicited increased activation in the right auditory cortex (which was not sensitive to the direction of the switch), but no switching effects were observed in the dorsolateral prefrontal cortex and the ACC. In our study, the task was pretty naturalistic in that participants read sentences, but it is plausible that the naturalistic task in Blanco-Elorrieta and Pylkkänen's design (2017) was even more naturalistic, thus the relative difference in the observed activation. However, most of the previous neural evidence (including Blanco-Elorrieta & Pylkkänen, 2016; 2017 and Abutalebi et al., 2007) has been collected from bilinguals who were not necessarily targeted as habitual code-switchers, or at least it was unclear as to whether they were. Our findings add to the current models by demonstrating that even for habitual code-switchers the control network proposed to be recruited for bilingual language control is recruited for the comprehension of sentential code-switches, even for individuals who code-switch on a daily basis within sentences. In addition, code-switched sentences activated the triangular portion of the left inferior frontal gyrus, including the superior frontal sulcus. These areas have been identified in Luk's et al., 2012 metanalysis as central areas for bilingual language control, and have been found to be active during bilingual language control during simultaneous interpreting (Hervais-Adelman et al., 2014) suggesting a general role during bilingual language control. The results also showed that code-switched sentences activated left angular gyrus and left dorsolateral prefrontal cortex, areas that also have been found active in inhibiting irrelevant semantic information (Lewis et al., 2019) and during a language switching tasks (Blanco-Elorrieta & Pylkkänen, 2017). As mentioned above, this design we did not directly compare the engagement of the control network when speakers comprehend single word switches (L1 to L2 and L2 to L1) but we focused on investigating the extent of control in place when comprehending switches that are embedded within a sentence, and critically when processing within sentence code-switches that are differentially represented in spontaneous speech. However, future directions of this work could include a direct comparison of single word switches to switches embedded in a sentential context. That design would enable to further test how the control network is engaged differentially when processing single word switches or switches embedded in sentences.

An interesting question is whether the control network is engaged differentially for the comprehension and production of code-switches. Blanco-Elorrieta et al. (2016) tested whether different networks are engaged while comprehending or producing single word language switches. They report that language-switching in production recruits primarily dorsolateral prefrontal regions (i.e., BAs 9, 10, and 46 bilaterally), while the comprehension of language switches engages the ACC, suggesting partially differential control networks for comprehension and production. Our results are in line with those finding showing that the comprehension (via reading) of code-switches recruit mid cingulate cortex, and no direct involvement of dorsolateral prefrontal regions was found.

Our results also show a general engagement of subcortical regions during the comprehension of code-switched sentences. For example, the processing of code-switched sentences elicited activity in the right caudate. Left caudate has been widely found to be active during bilingual language control (Abutalebi et al., 2016), and right caudate has been previously reported to be involved in bilingual language switching (Luk et al., 2011). Importantly, multilingual experience has also been found to change the right caudate volume (Hervais-Adelman, Egorova, & Golestani, 2017). Even though the observed activation was in right caudate, left caudate has been widely found to be active during bilingual language control (e.g., Abutalebi et al., 2016).

Similarly, the analyses also revealed that left fusiform, left inferior occipital gyrus and the left cerebellum were engaged while processing code-switched sentences. Left fusiform has been found to be implicated during silent reading (e.g., Mechelli et al., 2005), and during word recognition (Mainy et al., 2008), and right and left cerebellum have been implicated in language control through lesion studies showing that cerebellar damage induces language control deficits (Fabbro, Moretti, & Bava, 2000). Our results are also in line with the Adaptive Control model (Green & Abutalebi, 2013) that proposes a connection between the right cerebellum and frontal cortex areas as crucial for bilingual language control, especially for speakers in a dense code-switching environment (Green & Abutalebi, 2013). More recent models of bilingual language neuroplasticity that take into account variability in bilingual experience (e.g., Grundy, Anderson, & Bialystok, 2017; Pliatsikas, 2019; Deluca, Segaert, Mazaheri, & Krott, 2020) connect changes in cerebellar activity as a neural correlate of increased efficiency in response to differential types of bilingual experience, such that increased automaticity in bilingual language control might be associated with initial structural changes in frontal control regions which subsequently then decrease, while structural changes in more subcortical posterior regions (such as cerebellum) occur. In line with those models, our findings reveal functional activation in left cerebellar regions. Even though our results did not show right cerebellar activity, it is possible that the extent to which the cerebellum is implicated in processing code-switched language is modulated by experience, but also by the modality in which those switches are processed (i.e., spoken vs reading comprehension).

A critical goal of this study was to see if the statistical regularities of different types of sentential code-switches as observed in naturalistic corpora (Deuchar, 2012) are reflected in differential activations. Our results demonstrated sensitivity to the statistical regularities of the processed code-switches. Noun boundary switches elicited greater activation than switches at the verb boundary, in the left fusiform, the right calcarine fissure, and in the left occipital gyrus. Left fusiform has been reported to be active during non-verbal conflict resolution in bilinguals (Abutalebi et al., 2012), suggesting that habitual code-switchers engage greater conflict monitoring for less frequent code-switches than for more regular code-switches. We also observed significant activation in the right calcarine fissure which has been implicated in complex visual processing, which is in line with the task that requited participants to silently reading sentences. As such, reading and processing less frequent code-switches such as switches at the noun phrase boundary elicited more activity in the visual area. Finally, activation in the left occipital gyrus is part of the primary visual cortex has also been previously implicated in phonological decoding, language reception (Dietz, Jones, Gareau, Zeffiro, & Eden, 2005) and grammatical processing. (Ardila, Bernal, & Rosselli, 2016). However, we interpret our findings in left occipital gyrus in terms of a potential visual difficult in processing the different types of code-switches.

Even though the sample size ($n = 19$) is rather limited and this could be considered a limitation, this study represents a first step into the investigation of how different types of bilingual engagement can shape the recruitment of neural control networks in habitual code-switchers. We propose a number of final considerations for future directions. Given the prevalence of sentential code-switching during spoken language comprehension and production, future studies could capitalize on larger samples, and rely on individual variability to ask how the engagement of the network is modulated by variability in code-switching performance. In addition, utilizing more naturalistic experimental paradigms as attempted in Blanco-Elorrieta and Pylkkänen (2016) and potentially utilizing real-time conversational paradigms would inform on the real-time behavioral and neural synergies that occur during conversational code-switching. As proposed by Blanco-Elorrieta and Pylkkänen (2017) bilinguals' comprehension of natural switches is governed by language-driven predictability effects, and the finding that processing more artificial switches recruits executive control areas, but the comprehension of more natural codeswitches does not (and engages the auditory cortex) further validates the notion that listening to natural codeswitched sentences is a more ecologically valid task than processing switches between unrelated items. In addition, an important question to unveil is to understand if proficient bilinguals who are not habitual code-switchers and are therefore not exposed to the statistical regularities of different types of code switches will show the same pattern of results, especially regarding the sensitivity to the different. Finally, understanding the adaptability of the neural system in the face of sustained linguistic behaviors such code-switching, and sensitivity to the statistic regularities encoded in those behaviors will be foundational to advance future research. Previous research has highlighted how bilingualism catalyzes functional and structural changes ranging from typical language networks but also neuroplastic changes extending to language independent executive control (EC) areas. For example, structural changes in the EC network have been observed in bilinguals in dorsal anterior cingulate cortex (Abutalebi et al., 2012), providing potential additional neural reserve for aging populations (Abutalebi et al., 2015; Zhang, Wu, & Thierry, 2020), suggesting overall that bilingual brains experience prolonged and enduring neurostructural plasticity.

So far, most of the proposed models that have described structural changes due to bilingualism have taken a rather static approach to those modulations (but see The Abutalebi & Green, 2016; Calabria, Costa, Green, & Abutalebi, 2018; Green & Abutalebi, 2013 for how neural changes might be modulated by intensity of bilingual experience). It is only more recently, with a growing body of literature capitalizing on the importance of variability in bilingual experience not only from a quantitative but qualitative perspective that models of neurofunctional and structural effects of bilingualism incorporate a dynamic view of how those changes might occur. Two notable very recent models that explicitly incorporate variability in bilingual experience to explain neurofunctional changes are the Dynamic Restructuring Model (Pliatsikas, 2019), and the Unifying the Bilingual Experience Trajectories, (UBET) (Deluca et al., 2020). Both models discuss how structural dynamic changes occur in the face of differential sustained bilingual behavior, connecting the various neurocognitive adaptations to different aspects of bilingual experience, including code-switching. Further research will need to address how even finer linguistic regularities found in different bilingual language modes, including differences in code-switching can shapes that plasticity.

4. Conclusion

This study reveals the neural underpinnings of bilingual language control when habitual code-switchers read code-switched sentences. We demonstrated that even habitual code-switchers engage a number of areas within the general control network postulated for bilingual language control, even engaging neural areas, such as the cerebellum, that have been proposed to be critical for speakers who experience dense code-switching environments. Finally, we demonstrate for the first time that the neural network engaged by habitual code-switchers in the comprehension of code-switched sentences is sensitive to the linguistic regularities of those switching patterns.

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CRediT authorship contribution statement

Eleonora Rossi: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Paola E. Dussias:** Conceptualization. **Michele Diaz:** Conceptualization, Writing - original draft, Formal analysis. **Janet G. van Hell:** Conceptualization. **Sharlene Newman:** Data curation, Writing - original draft, Formal analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroling.2020.100938.

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