

Differential recruitment of executive control regions during phonological competition in monolinguals and bilinguals



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ABSTRACT

Behavioral research suggests that monolinguals and bilinguals differ in how they manage within-language phonological competition when listening to language. The current study explored whether bilingual experience might also change the neural resources recruited to control spoken-word competition. Seventeen Spanish–English bilinguals and eighteen English monolinguals completed an fMRI task in which they searched for a picture representing an aurally presented word (e.g., “candy”) from an array of four presented images. On competitor trials, one of the objects in the display shared initial phonological overlap with the target (e.g., *candle*). While both groups experienced competition and responded more slowly on competitor trials than on unrelated trials, fMRI data suggest that monolinguals, but not bilinguals, activated executive control regions (e.g., anterior cingulate, superior frontal gyrus) during within-language phonological competition. We conclude that differences in how monolinguals and bilinguals manage competition may result from bilinguals’ more efficient deployment of neural resources.

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1. Introduction

Spoken word comprehension is an incremental process – auditory information unfolds over time, partially activating multiple lexical candidates (Marslen-Wilson, 1987). For example, as the word “candy” is heard, the unfolding phonemes “c-a-n-...” lead to the activation of words including “can” and “candle,” which compete for selection (Alloppenna, Magnuson, & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Managing this competition is critical to spoken-word comprehension because a word cannot be properly understood and processed until a target has been selected. Although both monolinguals (e.g., Alloppenna et al., 1998; Tanenhaus et al., 1995) and bilinguals (e.g., Marian & Spivey, 2003a, 2003b) experience lexical competition during spoken-language comprehension, behavioral evidence suggests that it may be managed differently by the two groups (Blumenfeld & Marian, 2011). Specifically, enhanced executive control abilities (e.g., Bialystok, 2006, 2008; Costa, Hernández, & Sebastián-Gallés, 2008; Martin-Rhee & Bialystok, 2008; Prior & MacWhinney, 2009; but see Hilchey & Klein, 2011; Paap & Greenberg, 2013) may aid bilinguals’ ability to suppress incorrect lexical items. As

a result, bilinguals’ management of phonological competition may be more efficient than monolinguals’, not only as indexed by eye-movements (Bartolotti & Marian, 2012; Blumenfeld & Marian, 2011), but also neurally.

Bilingualism has already been shown to result in functional and structural changes to the human brain. For example, learning a second language leads to increased grey matter density in the left inferior parietal cortex (Mechelli et al., 2004) and affects how language processing regions (specifically left inferior frontal cortex) are recruited (Kovelman, Baker, & Petitto, 2008). Even for non-language based tasks, bilingualism can affect the neural underpinnings of attentional processes such as ignoring irrelevant visual information (Bialystok et al., 2005; Luk, Anderson, Craik, Grady, & Bialystok, 2010).¹ Although controlling interference in the non-linguistic visual domain manifests in different cortical patterns in monolinguals than in bilinguals (Abutalebi et al., 2012; Bialystok et al., 2005; Gold, Kim, Johnson, Kryscio, & Smith, 2013; Luk et al., 2010), and though controlling competition has been tied

¹ While recent research has questioned the pervasiveness of a bilingual advantage on behavioral executive control tasks (e.g., Hilchey & Klein, 2011; Paap & Greenberg, 2013), cortical changes may emerge even in the absence of behavioral differences (e.g., Bialystok, Luk, Olsen, & Grady, 2013; Rodríguez-Pujadas et al., 2013). Further research is necessary to clarify the neural underpinnings of possible behavioral advantages in bilinguals’ executive control abilities (e.g., Bialystok, 2006; Bialystok, 2008; Costa et al., 2008; Martin-Rhee & Bialystok, 2008; Prior & MacWhinney, 2009).

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to bilinguals' management of phonological competition (Blumenfeld & Marian, 2011), potential differences in the neural resources that monolinguals and bilinguals recruit to manage language coactivation have never been explored.

Past research has shown that native English speakers activate a number of frontal and temporal language regions in response to phonological competition (Righi, Blumstein, Mertus, & Worden, 2010). Specifically, Righi and colleagues found that phonological competition manifested in activation of left supramarginal gyrus (SMG), a region involved in phonological processing (e.g., Gelfand & Bookheimer, 2003). They also found activation of left inferior frontal gyrus (IFG), which the authors argue plays a role in processing lexical competition that arises at the phonological level. In addition to these language regions, we expect that frontal control areas will also be involved in the management of phonological competition. Particularly, we expect to see differences in how monolinguals and bilinguals recruit domain-general executive regions (e.g., prefrontal cortex) to manage phonological competition, consistent with observations that the groups differ in the neural control of non-linguistic competition (Abutalebi et al., 2012; Bialystok et al., 2005; Gold et al., 2013; Luk et al., 2010).

In order to determine whether monolinguals and bilinguals differ in the executive control resources they recruit to manage phonological competition, the current study employs a modification of the visual world paradigm, adapted for use with a button-box within a functional magnetic resonance imaging (fMRI) scanner. As participants hear an object's name and search for that object from an array of four images, their neural responses are expected to differ when an object in the search display shares initial phonological overlap with the presented name of the target (e.g., *candy* – *candle*) compared to when it does not (e.g., *candy* – *snowman*). Specifically, in the presence of phonological overlap, we expect to see recruitment of general executive control regions including prefrontal cortex and anterior cingulate. However, the recruitment of frontal-executive regions is expected to vary between monolinguals and bilinguals, as we hypothesize that bilinguals' behavioral efficiency at managing phonological competition (Blumenfeld & Marian, 2011) reflects increased efficiency in cortical regions required for executive control.

Neuroimaging research has examined bilinguals' recruitment of executive control to manage switching between their two languages (for a review see Hervais-Adelman, Moser-Mercer, & Golestani, 2011). This has included research in both the production (e.g., Abutalebi et al., 2008; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000) and comprehension (e.g., Abutalebi et al., 2007) domains. The link between executive control resources and the management of competition within a single language, however, remains unknown. Because bilinguals rely on efficient neural mechanisms for non-linguistic executive control (e.g., Abutalebi et al., 2012), and because non-linguistic inhibition has been behaviorally tied to the management of phonological competition (Blumenfeld & Marian, 2011), we propose that bilinguals will recruit an efficient network of control regions to overcome within-language competition.

2. Methods

2.1. Participants

Seventeen Spanish–English bilinguals and eighteen English monolinguals participated in the current study. All participants were recruited from the University of Houston and were right-handed, healthy adults ranging in age from 18 to 27, with normal or corrected-normal vision and no history of neurological or psychiatric illness. Language group was determined by

Table 1
Cognitive and linguistic participant demographics.

Measure	Monolinguals	Bilinguals
<i>N</i>	18; 6 male	17; 3 male
Age	22.28 (3.69)	21.00 (2.88)
Years of formal education	16.70 (0.88)	15.94 (1.43)
Grade point average	3.22 (0.45)	2.92 (0.42)
English age of acquisition (LEAP-Q)	Birth	4.88 (1.96)
Spanish age of acquisition (LEAP-Q)	–	Birth
English proficiency (LEAP-Q)	9.94 (0.24)	9.68 (0.58)
Spanish proficiency (LEAP-Q)	–	8.71 (0.82)
English current exposure (%; LEAP-Q)	100.00 (0.00)	60.31 (17.27)
Spanish current exposure (%; LEAP-Q)	–	39.69 (17.27)
English ability (Woodcock)	83.99 (7.54)	79.48 (4.68)
Spanish ability (Woodcock-Muñoz)	–	77.35 (6.83)
Comprehensive Test of Phonological Processing (CTOPP) digit span	17.67 (1.91)	15.59 (2.67)
Comprehensive Test of Phonological Processing (CTOPP) non-word repetition	13.78 (3.42)	14.06 (1.52)
Simon effect (ms)	38.10 (28.80)	33.30 (23.90)
Simon facilitation score (ms)	23.35 (14.38)	15.41 (21.93)
Simon inhibition score (ms)	14.76 (29.88)	17.86 (12.55)

Note: Values represent means. Those in parentheses represent standard deviations.

* Group difference at $p < .05$.

responses on the *Language Experience and Proficiency Questionnaire* (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007). Bilinguals were exposed to both English and Spanish by the age of eight and reported a proficiency of at least 7 on a scale from 0 (none) to 10 (perfect). Monolinguals did not report knowing any language other than English. Participants were matched on education level (years of formal education) and grade point average; see Table 1 for participant demographics and comparisons.

2.2. Design and materials

The current study followed a 2×2 design with language group (monolingual, bilingual) as a between-subjects variable and trial type (competitor, unrelated) as a within-subjects variable.

Twenty competitor sets were constructed, each comprised of an English target word (e.g., *candy*), a competitor whose name overlapped phonologically with the onset of the target (e.g., *candle*), and two filler items whose names shared no phonological overlap with any other items in the set. Targets and competitors shared an average of 2.40 phonemes ($SD = 0.68$). All stimuli were controlled to ensure that they did not overlap in Spanish phonological onset. Twenty unrelated sets were constructed by replacing the competitor with an item whose name did not overlap with the target; in unrelated sets, none of the four items shared phonological overlap. An additional 40 sets were created to use as filler trials to prevent participants from becoming aware of the phonological overlap present in competitor trials (consistent with experimental designs of visual world studies; e.g., Dahan & Tanenhaus, 2004; Marian & Spivey, 2003a, 2003b; Salverda & Tanenhaus, 2010).

All critical stimuli (targets, competitors, unrelated items, and filler items from each set) were matched on word frequency (*SUBTLEXUS*; Brysbaert & New, 2009), orthographic and phonological neighborhood size (*CLEARPOND*; Marian, Bartolotti, Chabal, & Shook, 2012), and concreteness, familiarity, and imageability (*MRC Psycholinguistic Database*; Coltheart, 1981) (all $ps > .05$). Target, competitor, and unrelated stimuli are provided in the Appendix.

Black and white line drawings were obtained for each item from the International Picture Naming Project (IPNP) database (Bates et al., 2000) or Google Images. Pictures from the IPNP were chosen according to high naming consistency norms by native English and

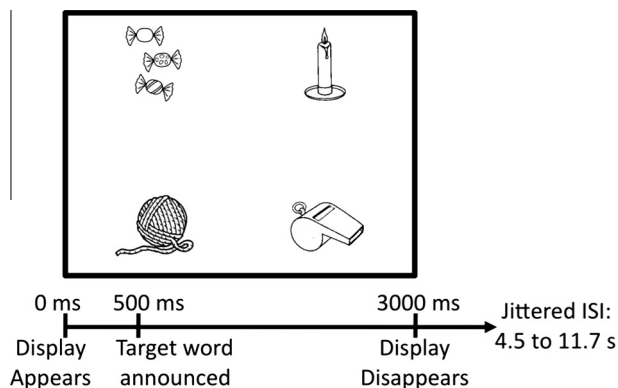


Fig. 1. Structure of competitor trials. On this display, the target (*candy*) is presented along with a phonological competitor (*candle*) and two unrelated pictures (*yarn*, *whistle*). Unrelated trials followed the same timing and layout, but the phonological competitor was replaced by an item whose name did not overlap with the name of the target (e.g., *snowman*).

native Spanish speakers; pictures from Google Images were independently normed by English monolinguals and Spanish–English bilinguals on Amazon Mechanical Turk (<https://www.mturk.com>). Naming reliability was 92% ($SD = 10.8$) in English and 84% ($SD = 16.4$) in Spanish.

Images were presented in the four corners of the screen at a visual angle of 13–15°. The location of the target was counterbalanced across trials, with each target occupying the same quadrant across competitor and unrelated conditions. The competitor/unrelated item always appeared adjacent to the target, with location counterbalanced across trials. Pictures appearing in the same display were controlled for visual similarity along the dimensions of shape (i.e., a pencil and a finger did not appear in the same display), saturation (i.e., no single image had areas that were noticeably darker), and line thickness (see Fig. 1).

The 80 trials (20 competitor, 20 unrelated, 40 filler) were arranged in a pseudo-randomized order that was fixed between participants. The pseudorandom order was designed such that targets appeared in each of the four quadrants an equal number of times and no image was seen more than once in three consecutive trials.

2.3. Procedure

Testing for the current study took place in two sessions: one for cognitive and behavioral assessments and one for the completion of the fMRI task. In the first session, participants gave informed consent on a protocol approved by a Human Subjects Committee. A trained experimenter administered cognitive measures and screened participants for claustrophobia, health conditions, and presence of metal in the body.

Language proficiency was assessed using the picture vocabulary and passage comprehension sections of the *Woodcock Language Proficiency Battery-Revised* (Woodcock, 1995) and the *Woodcock-Muñoz Language Survey-Revised* (Woodcock, Muñoz-Sandoval, Ruff, & Alvarado, 2005). Executive control was assessed using three measures derived from a colored squares version of the Simon Task (Simon & Rudell, 1967): the Simon effect, the facilitation effect, and the inhibition effect. The Simon effect was calculated by subtracting mean reaction time on congruent trials from mean reaction time on incongruent trials; the facilitation effect was calculated by subtracting mean reaction time on congruent trials from mean reaction time on neutral trials; and the inhibition effect was calculated by subtracting reaction times on neutral trials from mean reaction time on incongruent trials. Phonological

working memory was measured using the digit span and non-word repetition subtests of the *Comprehensive Test of Phonological Processing* (CTOPP; Wagner, Torgesen, & Rashotte, 1999). See Table 1 for group comparisons.

On the day of scanning, participants were familiarized with the fMRI scanner and were given sound dampening headphones to reduce scanner noise, a squeeze ball to signal the technician in case of emergency, and a button box to use to respond during the task. A four-image display was projected onto a mirrored screen, and participants received auditory instructions over the headphones to locate one of the four images.

Each trial began with presentation of the visual search display. After 500 ms, participants heard an English auditory presentation of the target stimulus (recorded by a male professional voice actor² at 48 kHz, amplitude-normalized). The search display remained on the screen for 2500 ms. Participants were instructed to indicate the target's location using a button box with four buttons. Each response quadrant was assigned to a single response button (the top left button corresponded to the top left quadrant, the top right button to the top right quadrant, etc.). Stimuli were presented in an event-related design using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) with an inter-stimulus interval ranging from 4.5 to 11.7 s (timing and stimuli presentation were consistent with previous visual world studies using fMRI; e.g., Righi et al., 2010). See Fig. 1 for a sample trial structure.

At the conclusion of the experiment, participants provided names for all competitor and unrelated pictures. Trials in which participants provided an alternate name that changed condition assignment (e.g., naming the *candle* from the *candy-candle* trial a “flame”) were removed from analysis (7.4% of trials).

2.4. Neuroimaging parameters

Functional neuroimaging data were collected at Baylor College of Medicine's Human Neuroimaging Laboratory using a 3.0 Tesla head-only Siemens Magnetom Allegra magnetic imager. Anatomical images were acquired using high-resolution T₁-weighted anatomical scans with an MPRAGE sequence at a voxel size of 1.0 × 1.0 × 1.0 mm, TR = 1200 ms, TE = 2.93 ms, reconstructed into 192 slices. Functional images were acquired in 34 axial slices parallel to the AC-PC line with an interleaved descending gradient recalled echo-planar (EPI) imaging sequence with a voxel size of 3.4 × 3.4 × 4.0 mm, TR = 2700 ms, and TE = 28 ms.

2.5. Data analysis

Three dependent measures were collected in the current study: accuracy, response time, and the blood-oxygen-level dependent (BOLD) response as indexed by fMRI. The dependent variables and the analysis techniques used to evaluate them are described below. For all analyses, trials in which no response was made (1.4% of trials) or in which participants provided an incorrect name

² All stimuli were recorded by a male Spanish–English bilingual voice actor. The speaker had no discernible accent in either English or Spanish, and participants were not told of the speaker's bilingual status. To ensure that the speaker's accent would not lead to Spanish activation, the speaker's English accent was independently evaluated by twelve native English speakers (who were not participants in the current study). Raters were provided with audio files of four speakers (in counterbalanced order) reciting the Rainbow Passage (Fairbanks, 1960) and were asked to evaluate the speakers' accents in three questions: (1) Please evaluate the speaker's accent on a scale from 1 (“Native English speaker, no foreign accent”) to 4 (“Strong foreign accent”); (2) How much of a foreign accent does this speaker have when speaking English? (“None”, “Light”, “Considerable”, “Pervasive”); (3) Is this person a native English speaker? (“Yes”, “No”). All twelve raters evaluated the accent of the voice actor as “Native English speaker, no foreign accent,” all twelve rated him as having no foreign accent when speaking English, and all twelve reported him to be a native English speaker.

for a critical item during post-experimental testing (7.4% of all trials) were removed.

2.5.1. Accuracy and response time

Accuracy and response time in the fMRI task were determined by button-box responses. Trials were considered accurate if the button pressed corresponded to the quadrant in which the target was located. Response time was measured from the onset of the search display to the point of the button-press response. Accuracy and response time scores were compared between language groups and across trial types using linear mixed effect (LME) regression models. The LME models included subject and item as random effects, and group (monolingual, bilingual), condition (competitor, unrelated), and item order (to control for potential order effects, as target items appeared on both competitor and unrelated trials) as fixed effects.

2.5.2. Functional neuroimaging

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

In first-level processing, the stimulus onsets for each condition (competitor, unrelated) were implicitly modeled against rest in each participant using a General Linear Model (GLM). Motion estimates from preprocessing were entered as covariates of no interest at the first-level to further control for motion artifacts, a method validated for use in event-related fMRI paradigms (Johnstone et al., 2006). A flexible factorial design including participant, group, and condition variables was used to assess the main effects and interactions of group (monolingual, bilingual) and condition (competitor, unrelated) in a 2×2 mixed effects ANOVA using a cluster-level FWE corrected threshold of $p < .05$. To reduce bias in follow-up analyses of individual effect sizes in task-identified regions of interest (ROIs), we used a leave-one-subject-out (LOSO) approach (Esterman, Tamber-Rosenau, Chiu, & Yantis, 2010). Thirty-five separate LOSO GLMs were performed, each with $n = 34$. Task-activated ROIs were identified in each model using a cluster-level FWE corrected threshold of $p < .05$. ROIs identified

in less than 10% of LOSO GLMs were not analyzed further. For each participant, mean beta weights for the competitor and unrelated contrasts were calculated in each ROI from the LOSO GLM that excluded that participant, thus preserving independence of ROI selection and measured task activation. Follow-up analyses examining the interaction between group and condition were also performed using paired or two-sample *t*-tests on the first-level contrast images at a threshold of $p < .001$, uncorrected, with a minimum of 10 voxels per cluster. Activation coordinates (MNI) were provided by SPM, and anatomical labeling was obtained from the Talarach atlas after conversion to Talarach coordinates (Lancaster et al., 1997, 2000).

Additionally, seven anatomical ROIs in prefrontal cortex were used to investigate the relationship between inhibitory control skill (i.e., Simon task performance) and cortical activation in response to linguistic competition. The ROIs were obtained from the MNI template and were selected based on their recruitment in executive control tasks: left and right inferior frontal gyrus (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Peterson et al., 2002), left and right middle frontal gyrus (Fan et al., 2003; Maclin, Gratton, & Fabiani, 2001), left and right superior frontal gyrus (Fan et al., 2003; Maclin et al., 2001), and anterior cingulate cortex (Fan et al., 2003; Kerns, 2006; MacDonald, Cohen, Stenger, & Cameron, 2000; Peterson et al., 2002). Mean beta weights for the competitor contrasts were obtained for each participant in each ROI. These mean beta weights were then correlated with participants' Simon effect, Simon inhibition, and Simon facilitation scores, separately within monolingual and bilingual groups.

3. Results

3.1. Accuracy and response time

Accuracy was high for all participants ($M = 97.6\%$, $SD = 4.0\%$) indicating that they were successfully able to complete the task. No group, condition, or order differences emerged, and there were no interactions (all $ps > .05$).

In response time, there were significant effects of condition ($t = 4.54$, $p < .001$, $\beta = 175.67$, $SE = 38.65$) and order ($t = 3.14$, $p < .01$, $\beta = 148.70$, $SE = 47.40$), and an interaction of condition and order ($t = 4.87$, $p < .001$, $\beta = -293.24$, $SE = 60.20$). Results indicated that targets were responded to faster in the second trial in which they appeared, and that competitor trials were responded to more slowly than unrelated trials (first viewing: competitor

Table 2
Effects of phonological competition in monolinguals and bilinguals.

Cortical region	Brodmann's area	Cluster size	MNI coordinates		
			x	y	z
<i>(A) Main effect of group</i>					
Monolingual > bilingual					
Left middle frontal gyrus/left inferior frontal gyrus	46/45	256	-38	32	22
Left superior frontal gyrus/medial frontal gyrus	10/9	255	-26	44	24
Left/right anterior cingulate	32	156	-4	34	28
Primary visual cortex	17	234	-4	-68	14
Bilingual > monolingual					
No suprathreshold clusters	-	-	-	-	-
<i>(B) Interaction of group and condition</i>					
Right parahippocampal gyrus	28	137	36	-2	-24
Left parahippocampal gyrus	28/34	132	-18	-14	-24
Left/right cerebellum	-	796	12	-44	-16
Middle cingulate	23/24	95	-6	-4	30

Note: Voxels thresholded at $p < .05$ (cluster level FWE corrected) with a minimum cluster size of $k = 10$ contiguous voxels. Coordinates and Brodmann's Areas listed indicate voxel with maximum intensity for that cluster in MNI space.

1838 ms, unrelated 1811 ms; second viewing: competitor 1693 ms, unrelated 1663 ms). There was no effect of group on RT and there were no interactions (all p s > .05).

3.2. Functional neuroimaging

Table 2 summarizes the results of the two-way mixed effects ANOVA on language group (monolingual, bilingual) and condition (competitor, unrelated). There was a significant main effect of group (A) and a significant interaction between group and condition (B).

The significant main effect of group showed that, compared to bilinguals, monolinguals displayed overall greater activation in frontal regions including anterior cingulate, left superior frontal gyrus, left inferior frontal gyrus, and left middle frontal gyrus, as well as in the primary visual cortex (see Table 2A and Fig. 2A).

Follow-up comparisons on the group by condition interaction, which manifested in the bilateral parahippocampal gyrus, middle cingulate, and the bilateral cerebellum (see Table 2B and Fig. 2B), revealed that in the unrelated-competitor contrast bilinguals activated bilateral parahippocampal gyrus and cerebellum less when a competitor was present than on control trials (see Table 3A). Furthermore, LOSO ROI analyses confirmed that when the competitor was present, bilinguals were less likely than monolinguals to activate the parahippocampal gyrus, cerebellum, and middle cingulate (see Fig. 3).

Because the purpose of the current research was to examine potential differences in how monolinguals and bilinguals recruit domain-general control resources in response to competition, we ran additional planned-comparisons on the competitor > unrelated contrast within groups. Within monolinguals, several clusters (including anterior cingulate, left superior frontal gyrus, and left middle temporal gyrus) were activated more in the competitor condition (e.g., *candy-candle*) than in the unrelated condition (e.g., *candy-snowman*) at a threshold of $p < .001$ uncorrected; bilinguals did not activate any additional brain regions in the competitor condition relative to the control condition (see Table 3B). In order to ensure statistical rigor, we restricted our interpretation to the

anterior cingulate and superior frontal gyrus – regions that reached statistical significance in the main effect of our 2-way ANOVA.

3.3. Correlations with inhibitory control

In order to determine whether the recruitment of cortical executive control networks was associated with better performance on general executive control tasks, we compared bilinguals' and monolinguals' performance on a non-linguistic executive control task (Simon task; see Table 1) and computed correlations between performance on the non-linguistic Simon task and performance on our linguistic competition task. Although the two language groups did not differ in their executive control abilities (monolinguals: $M = 38.10$ ms, $SD = 28.80$; bilinguals: $M = 33.30$ ms, $SD = 23.90$), individual participants' differences in reaction time between competitor and unrelated conditions (i.e., task interference) were correlated with their Simon effect scores ($R^2 = .11$, $p < .05$). Participants who were better able to overcome competition in the non-linguistic Simon task also experienced less interference from competition in the spoken-language task. This suggests that the control of linguistic and non-linguistic competition may be (at least partially) subserved by the same domain-general mechanisms.

Moreover, within-group correlations between Simon task performance and cortical activation during the language task revealed differences in how the two language groups recruited domain-general control mechanisms in response to linguistic competition. Within-group correlations compared Simon task performance (interference suppression, cue facilitation, and the Simon effect) and mean activation during competitor trials in seven prefrontal anatomical ROIs: left and right inferior frontal gyrus (IFG), left and right middle frontal gyrus (MFG), left and right superior frontal gyrus (SFG), and anterior cingulate cortex (ACC). In bilinguals, better interference suppression (i.e., smaller Simon inhibition scores) was correlated with increased brain activation during competitor trials in left MFG ($R^2 = .30$, $p < .05$) and right MFG ($R^2 = .31$, $p < .05$), in left SFG ($R^2 = .37$, $p < .05$) and right SFG ($R^2 = .37$, $p < .05$), as well as in right IFG ($R^2 = .30$, $p < .05$) and ACC

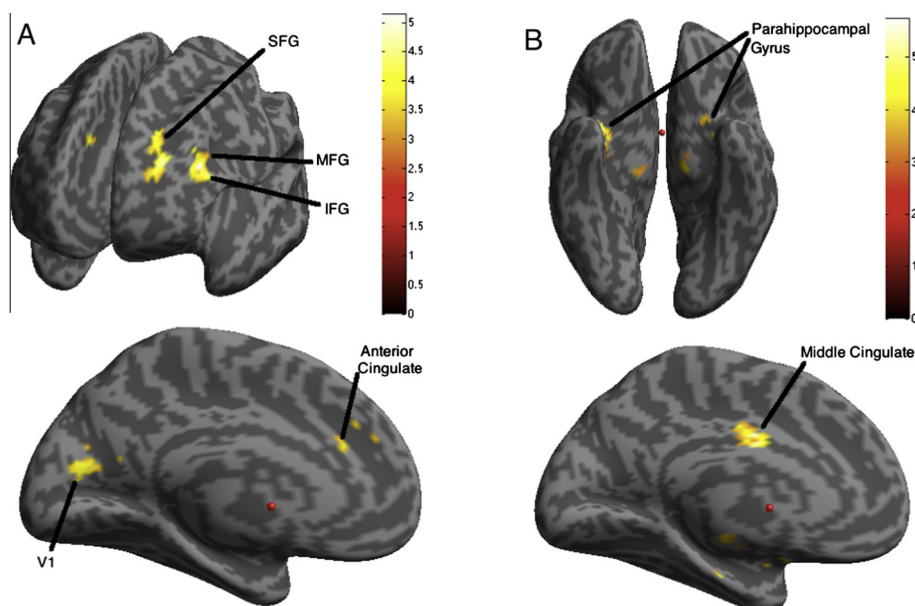


Fig. 2. Activated clusters in the Group \times Condition ANOVA. (A) Clusters showing greater activation for monolingual speakers of English compared to bilingual speakers of English and Spanish, including left superior frontal gyrus (SFG), left middle frontal gyrus (MFG), left inferior frontal gyrus (IFG), bilateral anterior cingulate, and primary visual cortex (V1). (B) Clusters showing an interaction of group by condition, including bilateral parahippocampal gyrus, middle cingulate, and bilateral cerebellum (not pictured).

Table 3Follow-up and planned comparisons for group \times condition interaction: competitor effects within language groups.

Cortical region	Brodmann's area	Cluster size	MNI coordinates		
			x	y	z
<i>(A) Unrelated > competitor (follow-up analyses)</i>					
Monolinguals					
No suprathreshold clusters	–	–	–	–	–
Bilinguals					
*Right parahippocampal gyrus	–	218	34	–10	–22
*Right parahippocampal gyrus	36	67	26	–32	–22
*Left parahippocampal gyrus	28	176	–20	–12	–26
*Left parahippocampal gyrus	36	36	–38	–30	–14
*Left parahippocampal gyrus	19	21	–30	–54	–2
*Right cerebellum	–	147	14	–48	–14
*Central cerebellum	–	11	0	–66	–2
Left inferior frontal gyrus	47	54	–28	12	–22
Right middle frontal gyrus	6	18	22	–10	52
Right medial frontal gyrus	6	12	6	–18	68
Right middle occipital gyrus	18	12	26	–80	0
Left sub-gyral occipital	–	51	–38	–58	–10
Left caudate	–	21	–14	10	26
Left extra-nuclear area	–	16	–34	–58	6
Right midbrain	–	57	2	–28	–24
<i>(B) Competitor > unrelated (planned comparisons)</i>					
Monolinguals					
*Right anterior cingulate	32	15	4	48	12
*Left superior frontal gyrus	10	13	–24	54	16
Left middle temporal gyrus/ superior temporal sulcus	21	15	–52	–46	4
Bilinguals					
No suprathreshold clusters	–	–	–	–	–

Note: Voxels thresholded at $p < .001$, $t = 3.646$ (monolinguals) or $t = 3.686$ (bilinguals), (uncorrected) with a minimum cluster size of $k = 10$ contiguous voxels. Coordinates and Brodmann's Areas listed indicate voxel with maximum intensity for that cluster in MNI space.

* Asterisks represent regions identified in the 2×2 ANOVA.

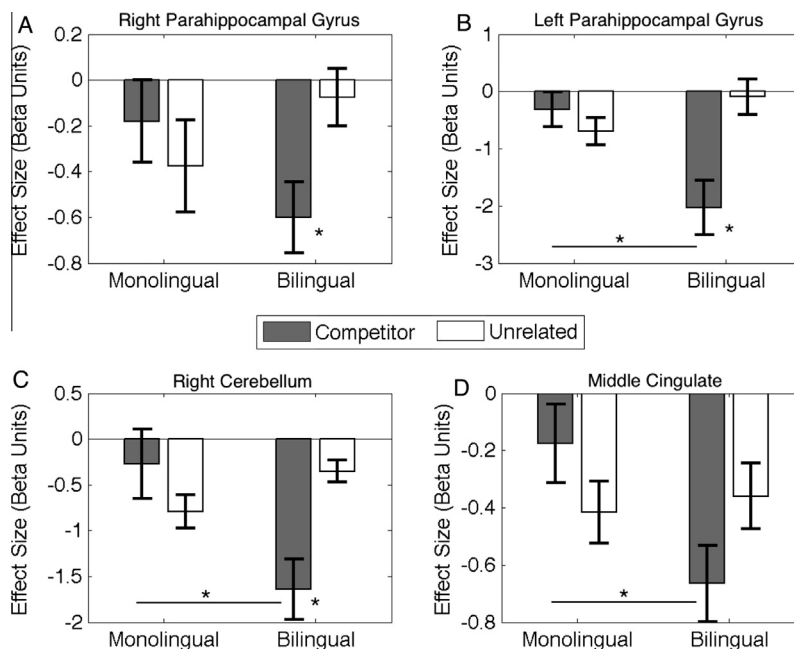


Fig. 3. Mean effect size in task-activated ROIs identified in the interaction of Group \times Condition. ROIs for each participant were created based on task activation from a GLM excluding that participant using a Leave One Subject Out methodology to preserve independence of ROI definition and measured activation. (A) Bilinguals deactivated right parahippocampal gyrus in competitor trials more than unrelated trials, (B) bilinguals deactivated left parahippocampal gyrus in competitor trials more than unrelated trials, and more than monolinguals, (C) bilinguals deactivated right cerebellum in competitor trials more than unrelated trials, and more than monolinguals, (D) bilinguals deactivated middle cingulate in competitor trials more than monolinguals. Asterisks indicate significance at $p < .05$.

($R^2 = .28$, $p < .05$). In contrast, in monolinguals, better interference suppression was only correlated with increased brain activation during competitor trials in right MFG ($R^2 = .30$, $p < .05$). No signifi-

cant correlations were found between language task activation and cue facilitation or between task activation and Simon effect scores for either group (all $ps > .05$).

4. Discussion

In the present study, the neural bases of phonological competition were explored in monolinguals and bilinguals. While both groups experienced competition, as indexed by slower response times in competition conditions relative to unrelated conditions, we demonstrate for the first time that monolinguals and bilinguals recruit different neural resources to manage this competition. Specifically, within-group comparisons suggest activation of executive control regions (e.g., anterior cingulate, left superior frontal gyrus) during phonological competition in monolinguals, but not in bilinguals.

Reaction time measures revealed that, while responses were slower overall on competitor trials, bilinguals did not manage this competition any more quickly than did monolinguals. Because reaction time measures require motoric responses, they may not be sensitive enough to capture between-group differences. In fact, reaction time often fails to detect differences between monolinguals' and bilinguals' responses to competition, even when other behavioral measures (such as eye-tracking or mouse-tracking) indicate group differences (e.g., Bartolotti & Marian, 2012; Blumenfeld & Marian, 2011). Instead, more sensitive measures, such as eye-tracking or functional neuroimaging are needed to highlight meaningful differences in how monolinguals and bilinguals manage phonological competition. Here, we demonstrate that, even in the absence of behavioral differences between groups, monolinguals and bilinguals differ in the cortical resources recruited to manage phonological competition.

In contrast to the increased recruitment of language and executive control regions observed by Righi et al. (2010) in competitor trials, participants in our current study showed limited activation in response to direct manipulations of competition. This is likely due to differences between the populations tested in the two studies. Although Righi et al.'s sample was not explicitly controlled for language experience, all participants were native English speakers. In contrast, our current study includes both native English speakers (monolinguals) and native Spanish speakers (bilinguals). When we consider only monolingual subjects, the group likely most analogous to the participants used by Righi et al., competitor effects emerge in executive control regions such as the anterior cingulate (Milham et al., 2001) and superior frontal gyrus (du Boisgueheneuc et al., 2006), though activation in linguistic areas remained unaffected by competition.

The most striking finding from the current study is that bilinguals displayed substantially less cortical activation compared to monolinguals throughout the duration of the task. A main effect of group illustrated that monolinguals (but not bilinguals) recruited a network of executive control areas (e.g., left superior frontal gyrus: du Boisgueheneuc et al., 2006; anterior cingulate: Milham et al., 2001; left inferior frontal gyrus: e.g., Swick, Ashley, & Turken, 2008; left middle frontal gyrus: e.g., Milham et al., 2002) and primary visual cortex while completing the task. This broad activation in monolinguals is also supported by a significant group by condition interaction and planned comparisons showing that, specifically in response to competition, monolinguals recruited anterior cingulate and left superior frontal gyrus. Such extensive reliance on executive control regions, particularly when confronted with linguistic competition, suggests that monolinguals' management of phonological competition is not automatic, but rather requires the allocation of domain-general cognitive resources. Moreover, because this increase in activation is strongest in monolinguals when competition is present, these differences between language groups can be attributed to how competition was managed and not to basic language processing.

Monolinguals' (and not bilinguals') reliance on cortical areas associated with visual processing (i.e., primary visual cortex) is likely also indicative of less automatic processing in monolinguals. Primary visual cortex (V1) has been implicated in attentional processing, even within purely auditory domains (e.g., Jack, Shulman, Snyder, McAvoy, & Corbetta, 2006; see Kleinschmidt, 2006 for an extended review). Therefore, in our language-based task, in which visual attention must be allocated to the target object while ignoring distracting alternatives, monolinguals may experience more attentional demands than do bilinguals, thereby increasing their reliance on V1 to direct attention and control interference.

In contrast to the pattern observed in monolinguals, bilinguals recruited fewer cortical resources when competition was present. Specifically, bilinguals activated the parahippocampal gyrus and cerebellum less in the competitor condition compared to the unrelated condition. Decreased BOLD activity in the parahippocampal gyrus has been linked to enhanced performance on visual target-finding tasks that require sustained attention (Lawrence, Ross, Hoffmann, Garavan, & Stein, 2003). This finding may suggest that when task demands are higher, as in the competition condition, bilinguals successfully reduce activation of task-irrelevant regions, thereby efficiently modulating sustained attention mechanisms to manage competition. Activation of the cerebellum is less understood, though its involvement in language-processing tasks is often observed (e.g., Binder et al., 1997; Booth, Wood, Lu, Houk, & Bitan, 2007; Desmond & Fiez, 1998). Because the cerebellum is directly connected to and involved in the modulation of brain regions including the inferior frontal gyrus (Booth et al., 2007), a decrease in cerebellar activation is consistent with bilinguals' lack of reliance on frontal-executive regions to manage competition.

A reduction in parahippocampal and cerebellar activation by bilingual participants may also reflect bilinguals' expertise in mapping the incoming auditory stream to the visually-presented items. In a study of musicians and non-musicians, participants with expertise in audio-visual matching (drummers) displayed less activation of parahippocampus and cerebellum than non-experts when viewing displays that matched with incoming auditory information (Petrini et al., 2011). Like musicians, bilinguals may be experts at integrating audio-visual information (Chabal & Marian, *in press*; Marian, 2009), and therefore may more efficiently deploy cortical resources in response to auditory and visual inputs. As with musicians in Petrini and colleagues' study, this efficiency is especially evident in more difficult trials (i.e., when phonological competition is present).

Together, findings of competitor activation in monolinguals but not bilinguals suggest that bilinguals may be more efficient at managing phonological competition. This interpretation is consistent with behavioral research suggesting that executive control mechanisms may be more efficient in bilinguals compared to monolinguals (e.g., Treccani, Argyri, Sorace, & Della, 2009). Most relevant to the current study are Blumenfeld and Marian's (2011) findings that bilinguals' (but not monolinguals') inhibition of competing phonological information is associated with the group's executive control ability. Here, we show that the behavioral differences observed between monolinguals and bilinguals in past research may indeed be driven by differences in how the groups recruit executive control resources at the neural level.

Although monolinguals and bilinguals in our study did not differ in their behavioral Simon effect performance (as participants were young adults at their cognitive peak; see Hilchey & Klein, 2011), cortical changes attributed to language experience emerge

even in the absence of behavioral differences between groups (e.g., Bialystok et al., 2013; Rodríguez-Pujadas et al., 2013). Accordingly, we observed significant correlations between performance on a non-linguistic competition task and cortical activation in regions associated with executive control during a linguistic competition task.

Past research has demonstrated that non-linguistic competition is managed through the recruitment of frontal cortical regions including middle frontal gyrus (MFG; Fan et al., 2003; Maclin et al., 2001), superior frontal gyrus (SFG; Fan et al., 2003; Maclin et al., 2001), anterior cingulate cortex (ACC; Fan et al., 2003; Kerns, 2006; MacDonald et al., 2000; Peterson et al., 2002), and inferior frontal gyrus (IFG; Fan et al., 2003; Peterson et al., 2002). When faced with *linguistic* competition, the bilinguals who were best at resolving *non-linguistic* competition were most likely to strongly activate this extended network of frontal regions. Specifically, correlations between non-linguistic competition resolution and the control of linguistic competition were found in bilateral MFG, bilateral SFG, right IFG, and ACC. This suggests that, in bilinguals, the substrates used to resolve linguistic and non-linguistic competition are highly related. In other words, bilinguals rely on inhibitory control processes that are modality- and task-independent. Monolinguals, in contrast, appear to rely on partially distinct mechanisms for the control of linguistic and non-linguistic competition. Unlike the bilinguals, for whom correlations emerged in multiple distinct regions associated with executive control (bilateral MFG, bilateral SFT, right IFG, ACC), monolinguals' performance only resulted in significant correlations in right MFG.

The finding that bilinguals', but not monolinguals', cortical control of linguistic competition is subserved by domain-general control mechanisms is consistent with both neuroimaging (Garbin et al., 2010) and behavioral (Blumenfeld & Marian, 2011) evidence that linguistic and non-linguistic competition are related in bilinguals but not in monolinguals. It is also consistent with research demonstrating correlations between non-linguistic executive control measures and neurological responses in bilingual populations (Krizman, Marian, Shook, Skoe, & Kraus, 2012).

Bilinguals' executive control abilities are likely honed by the constant need to suppress irrelevant language information. Because both of a bilingual's languages are simultaneously activated when processing both auditory (e.g., Marian & Spivey, 2003a, 2003b; Shook & Marian, 2012) and visual (e.g., Chabal & Marian, 2013; Van Heuven, Dijkstra, & Grainger, 1998; Van Heuven, Schriefers, Dijkstra, & Hagoort, 2008) input, information from the language not currently in use must be ignored. Moreover, not only must bilinguals attend to the language they are currently using, but they also must contend with extra sources of phonological competition. In addition to the competition experienced by monolinguals within their single language (e.g., *marker-marbles* in English), bilinguals also must resolve competition that arises between their two languages (e.g., the English form *marker* competes with the Russian word *marka*, meaning "postage stamp"; Marian & Spivey, 2003a, 2003b). It is likely that, over time, the bilingual cognitive system has been tuned to deal with these sources of competing information. This tuning, as we have observed in the current study, manifests in more efficient deployment of neural resources.

The cortical efficiency with which bilinguals manage phonological competition is consistent with findings that bilinguals' neural responses to non-linguistic competition are also tuned. For example, bilinguals show less activation than monolinguals in anterior cingulate cortex during a spatial conflict monitoring task (Abutalebi et al., 2012). Importantly, this efficiency may protect bilingual adults from normal cognitive decline due to aging. Older age has been associated with decreases in cortical efficiency, as indexed by poorer task performance and greater activation in task-related regions (e.g., Colcombe, Kramer, Erickson, & Scaff, 2005; Park, Polk, Mikels, Taylor, & Marshuetz, 2001). However, this decline may be attenuated by bilingual language experience, as recent research has demonstrated that bilingual older adults require less activation in frontal regions than do their monolingual peers when confronted with a perceptual task-switching task (Gold et al., 2013). Therefore, our findings of efficient neural processing during linguistic competition are likely indicative of broad, lifelong cortical changes in bilingual populations.

An open question is whether the neural resources recruited by bilinguals to manage within-language phonological competition are the same as those used to control competition arising between languages. When competition occurs within a single language, we observe decreased activation of parahippocampal gyrus and cerebellum in response to competition. While it is likely that similar domain-general mechanisms underlie the control of competition regardless of the source of phonological overlap, as evidenced by significant correlations between participants' performance on our linguistic competition task and the non-linguistic Simon task, it is possible that different regions will be recruited when the overlap occurs across languages. When competition occurs between languages, inhibition of the non-target language is required. This may result in the recruitment of a larger executive control network compared to when competition emerges only within a single language. In fact, in the context of a written lexical decision task, between-language competition results in bilinguals' recruitment of cognitive control regions including pre-supplementary motor area and anterior cingulate (van Heuven et al., 2008). This pattern of activation may also be expected when cross-linguistic competition emerges in a spoken context. Future research will test this possibility by using fMRI to explore differences in how bilinguals respond to within- and between-language competition.

In conclusion, we have provided the first functional neuroimaging evidence that monolinguals and bilinguals differ in how they respond to within-language spoken-word competition. We illustrate that bilinguals' recruitment of executive control resources is less extensive than that of monolinguals, indicating that bilinguals' enhanced behavioral efficiency at overcoming language coactivation (Blumenfeld & Marian, 2011) is reflected in increased cortical efficiency.

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Appendix A

A.1. Target, competitor, unrelated, and filler stimuli

	Target	Competitor	Unrelated	Filler 1	Filler 2
1	antler (æntlər)	ant (ænt)	toe (tu)	raft (ræft)	spatula (spætjulə)
2	basket (bæskɪt)	bat (bæt)	lightning (laɪtnɪŋ)	hat (hæt)	diaper (daɪpər)
3	brain (breɪn)	bridge (brɪdʒ)	elevator (ɛləveɪtər)	king (kɪŋ)	glasses (glæsəs)
4	candy (kændi)	candle (kændl)	snowman (snoumæn)	hair (heɪr)	barbecue (bɑrbəku)
5	drum (drʌm)	dress (dres)	watering can (wɔtərɪŋ kæn)	knife (naɪf)	bear (beɪr)
6	sheep (ʃip)	shield (ʃɪld)	raccoon (rækun)	neck (nek)	buckle (bʌkl)
7	gun (gʌn)	gutter (gʌtər)	screw (skru)	walrus (wɔlrʌs)	tree (tri)
8	lighter (laɪtər)	lightning (laɪtnɪŋ)	cloud (klaʊd)	skateboard (skeɪtbɔrd)	toilet (tɔɪlət)
9	magnet (mæɡnɪt)	match (mætʃ)	witch (wɪtʃ)	pencil (pensl)	corn (kɔrn)
10	pig (pɪɡ)	picture (pɪktʃər)	ant (ænt)	fireplace (faɪrpleɪs)	roof (ruf)
11	rattle (rætl)	raccoon (rækun)	hummingbird (hʌmɪŋbɜrd)	bacon (beɪkən)	pillow (pɪləʊ)
12	elbow (ɛlbəʊ)	elevator (ɛləveɪtər)	bat (bæt)	hanger (hæŋər)	door (dɔr)
13	clown (klaʊn)	cloud (klaʊd)	match (mætʃ)	owl (aʊl)	log (lɔɡ)
14	honey (hʌni)	hummingbird (hʌmɪŋbɜrd)	shield (ʃɪld)	rice (raɪs)	dog (dɔɡ)
15	snail (sneɪl)	snowman (snoumæn)	dress (dres)	whisk (wɪsk)	lightbulb (laɪtblʌb)
16	flag (flæg)	flashlight (flæʃlaɪt)	picture (pɪktʃər)	rocking chair (rɔkɪŋ tʃeɪr)	staircase (steɪrkɛɪs)
17	scarf (skɑrf)	screw (skru)	candle (kændl)	ladder (lædər)	hot dog (hɔt dɔɡ)
18	toad (tuɔd)	toe (tu)	flashlight (flæʃlaɪt)	box (bɔks)	ice cream (aɪs kɪrɪm)
19	waterfall (wɔtərɔfɔl)	watering can (wɔtərɪŋ kæn)	bridge (brɪdʒ)	tape (teɪp)	moose (muːs)
20	wig (wɪɡ)	witch (wɪtʃ)	gutter (gʌtər)	lighthouse (laɪthaʊs)	eye (aɪ)

Note: Parentheses represent transcriptions according to the International Phonetic Alphabet (IPA).

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