

Parallel language activation and cognitive control during spoken word recognition in bilinguals

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Accounts of bilingual cognitive advantages suggest an associative link between crosslinguistic competition and inhibitory control. We investigate this link by examining English-Spanish bilinguals' parallel language activation during auditory word recognition and nonlinguistic Stroop performance. Thirty-one English-Spanish bilinguals and 30 English monolinguals participated in an eyetracking study. Participants heard words in English (e.g., *comb*) and identified corresponding pictures from a display that included pictures of a Spanish competitor (e.g., *conejo*, English *rabbit*). Bilinguals with higher Spanish proficiency showed more parallel language activation and smaller Stroop effects than bilinguals with lower Spanish proficiency. Across all bilinguals, stronger parallel language activation between 300 and 500 ms after word onset and reduced parallel language activation between 633 and 767 ms after word onset were associated with smaller Stroop effects. Results suggest that bilinguals who perform well on the Stroop task show increased crosslinguistic competitor activation during early stages of word recognition and decreased competitor activation during later stages of word recognition. Findings support the hypothesis that crosslinguistic competition impacts domain-general inhibition.

Keywords: Parallel language activation; Inhibition; Stroop task; Bilingualism; Eyetracking.

Bilinguals have been found to show fine-grained advantages in cognitive control relative to their monolingual peers. These advantages are becoming increasingly well-defined, and include aspects of cognitive control such as conflict resolution on Stroop (e.g., Bialystok, 2006; Bialystok, Craik, & Luk, 2008; Bialystok & DePape, 2009; Costa, Hernandez, Costa-Faidella, & Sebastian-Galles,

2009; Costa, Hernandez, & Sebastian-Galles, 2008; Hernandez, Costa, Fuentes, Vivas, & Sebastian-Galles, 2010; Luk, de Sa, & Bialystok, 2011) and Simon tasks (Bialystok, Craik, Klein, & Viswanathan, 2004; Salvatierra & Rosselli, 2011; Schroeder & Marian, 2012), conflict monitoring (Costa, Hernandez, et al., 2009; Tao, Marcecova, Taft, Asanowicz, & Wodniecka, 2011), and task

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switching (Prior & MacWhinney, 2010). Bilingual cognitive advantages are thought to emerge over time due to the cognitive demands of bilingual language processing (e.g., Bialystok & Craik, 2010; Green, 2011; Kroll, 2008), and are positively associated with number of years of functional bilingualism (Luk et al., 2011), with daily immersion in both language contexts (e.g., Tao et al., 2011), and with high bilingual proficiency (e.g., Singh & Mishra, 2012). The exact mechanisms of bilingual language processing that give rise to these cognitive benefits are not yet fully understood. Here, we link the coactivation of a nontarget language during spoken word recognition to enhanced control abilities.

A number of studies suggest direct links between cognitive control abilities and bilingual language processing (e.g., Kroll, Bobb, Misra, & Guo, 2008; Levy, McVeigh, Marful, & Anderson, 2007; Macizo, Bajo, & Martin, 2010; Martin, Macizo, & Bajo, 2010; Michael & Gollan, 2005; Misra, Guo, Bobb, & Kroll, 2012; Morales, Paolieri, & Bajo, 2011). For example, in the language production domain, Prior and Gollan (2011) reported better task-switching abilities in bilinguals who code-switch frequently than in bilinguals who do not code-switch, and Vega and Fernandez (2011) found that more balanced bilinguals made fewer perseveration errors on the Wisconsin Card Sorting Test. Correlations have also been identified between bilingual language processing and cognitive control tasks on which bilinguals have previously shown cognitive advantages. Linck, Schwieter, and Sunderman (2011) found that smaller switching costs from L2 or L3 into L1 correlated with smaller Simon effects (a marker of better inhibition abilities) in trilingual young adults. Moreover, crosslinguistic activation has been linked to inhibitory control abilities. For example, stronger crosslinguistic cognate activation and facilitation during naming have been associated with less efficient Simon inhibition (Linck, Hoshino, & Kroll, 2008). Similarly, more crosslinguistic intrusion errors during a verbal fluency task have been linked to increased errors in an incongruent condition of a flanker task in older bilinguals (Gollan, Sandoval, & Salmon, 2011). Using a composite inhibitory control measure including nonlinguistic Stroop, Simon, and antisaccade task performance, Pivneva, Palmer, and Titone (2012) showed that increased inhibition abilities in bilinguals were associated with overall more efficient speech planning and production in L1 and L2. Finally,

during learning, more efficient Simon performance has been associated with better implicit memory outcomes in high-interference contexts (Bartolotti, Marian, Schroeder, & Shook, 2011). Critically, in all of these correlational studies, *better* cognitive control was associated with *less* interference in the linguistic context, including less crosslinguistic activation. Interestingly, self-reports across these studies show moderate to high L2 proficiency and age of L2 acquisition between 5 to 10 years, suggesting that cognitive control mechanisms may be recruited for linguistic processing in bilinguals with varied proficiency and age of acquisition profiles.

Similar to language production in bilinguals, early evidence suggests that bilinguals' *receptive* language processing is also supported by cognitive control mechanisms (e.g., Kaushanskaya, Blumenfeld, & Marian, 2011; Linck et al., 2008). Recent evidence suggests that simultaneous bilinguals outperform their monolingual peers in ignoring irrelevant auditory input during listening (Krizman, Marian, Shook, Skoe, & Kraus, 2012; Soveri, Laine, Hämäläinen, & Hugdahl, 2010). Involvement of inhibitory control mechanisms has also been identified at the linguistic level, including findings that bilinguals inhibit crosslinguistic homographs and that such inhibition is recruited across a window of time that extends past the homograph stimulus (Macizo et al., 2010; Martin et al., 2010).

Findings from Blumenfeld and Marian (2011) also speak to the temporal aspects of inhibition during receptive language processing. In an English *within-language* task, bilinguals who demonstrated smaller Stroop effects showed less residual inhibition of phonological cohort competitors 500 ms after target identification (as indexed by priming probes). This correlation between phonological conflict resolution and performance on a nonlinguistic Stroop task was significant in bilinguals but not monolinguals. Differences between bilinguals and monolinguals were ascribed to bilinguals' need to resolve higher levels of linguistic conflict. Such linguistic conflict includes auditory cohort competitors *within-language*, which are present in both monolingual and bilingual listeners (Marian & Spivey, 2003a, 2003b; Marslen-Wilson, 1987). Yet, in bilinguals, even *within-language* processing may be more challenging due to the added contribution of simultaneous *between-language* competitors. Thus, bilinguals are confronted with a larger cohort of similar-sounding words during auditory recognition,

and may routinely recruit domain-general cognitive control mechanisms to meet expected linguistic needs.

Parallel language activation during auditory comprehension is a process that has been identified across various language contexts and proficiency levels, and may thus be a relatively ubiquitous source of increased competition during bilinguals' receptive language processing (Blumenfeld & Marian, 2007; Canseco-Gonzales et al., 2010; Cutler, Weber, & Otake, 2006; Ju & Luce, 2004; Marian, Blumenfeld, & Boukrina, 2008; Marian & Spivey, 2003a, 2003b; Weber & Cutler, 2004; Weber & Paris, 2004). In general, the most robust parallel language activation has been found in bilinguals who are highly proficient and currently immersed in the nontarget language (Blumenfeld & Marian, 2007). Such increased parallel activation is likely due to more automatic activation of representations as proficiency increases (Segalowitz & Hulstijn, 2005). However, even when bilinguals listen in their more proficient language, they are likely to experience at least occasional coactivation of their less proficient language (Blumenfeld & Marian, 2007; Ju & Luce, 2004). Coactivation of 2 languages has also been found in the presence of semantic contextual constraints (e.g., Chambers & Cooke, 2009; Schwartz & Kroll, 2006; Vandenberg, Guadalupe, & Zwaan, 2011). Together, findings suggest that nonselective language activation may occur across a range of proficiency levels and linguistic contexts, with the most reliable parallel language activation when the nontarget language is highly proficient. It can be concluded that crosslinguistic activation and conflict resolution permeate bilingual receptive language processing in everyday environments.

With a large body of evidence suggesting that parallel language activation is common during receptive processing in bilinguals, the question of how this competition is resolved remains under investigation. The current study provides a direct test of how bilinguals resolve competition during parallel language activation. We examine *crosslinguistic* activation and conflict resolution in bilinguals, and attempt to identify a link between language proficiency, parallel language activation (as indexed via eyetracking), and performance on the same nonlinguistic Stroop task that was used in the within-language study by Blumenfeld and Marian (2011). Eyetracking is a well-suited methodology to covertly index coactivation of similar-sounding words (e.g., English *comb*, Spanish *conejo*)

over time, including the subsequent deactivation of irrelevant word candidates (e.g., Marian & Spivey, 2003a, 2003b; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Phonological competition resolution may share a common cognitive control process with the nonlinguistic Stroop task because, in both cases, the perceived stimulus can be interpreted in 2 different ways. That is, perceptual/conceptual conflict is inherent to the stimulus, and this conflict must be resolved in order to yield the most appropriate interpretation (e.g., during phonological competition, the target word is *comb* not *conejo*; on the classic Stroop task, the ink colour is *red* not *blue*). This aspect of Stroop-type competition resolution, also referred to as stimulus–stimulus conflict (Kornblum, Stevens, Whipple, & Requin, 1999), is therefore a good candidate as a mechanism that may support crosslinguistic competition resolution in bilinguals.

THE PRESENT STUDY

In the present study, we aimed to relate bilinguals' crosslinguistic activation and competition resolution to performance on a nonlinguistic Stroop task. Identification of such a link would establish crosslinguistic competition resolution during comprehension as one source of the previously found bilingual advantage on Stroop-type tasks and would thus contribute to specification of the linguistic origins of bilingual advantages on cognitive control tasks. A bilingual visual world paradigm was employed to index parallel language activation during auditory word recognition, where English-Spanish participants heard words in English and identified corresponding pictures (e.g., *comb*) in the presence of cohort competitor pictures (e.g., *conejo*, Spanish for *rabbit*). Participants also completed a nonlinguistic spatial Stroop task (Blumenfeld & Marian, 2011, adapted from Liu, Banich, Jacobsen, & Tanabe, 2004). On this Stroop task, participants identified the *direction* of arrows (right or left) that appeared on the right or the left side of the screen, resulting in perceptual conflict (right vs. left) on trials where right-pointing arrows appeared on the left or left-pointing arrows appeared on the right. Neural correlates of a similar spatial Stroop task (Liu et al., 2004) have high overlap with neural correlates of cognitive control during bilingual language processing (Abutalebi, 2008), suggesting that similar cognitive mechanisms may

underlie the two. Moreover, bilingual experience has been shown to change the neural substrates of Stroop-type tasks, relative to monolinguals (Luk, Anderson, Craik, Grady, & Bialystok, 2010), suggesting that Stroop-type mechanisms may be recruited for bilingual language processing. Consistent with these previous findings, Blumenfeld and Marian (2011) found a link between Stroop inhibition and within-language competition resolution in bilinguals. Therefore, the spatial Stroop task was chosen since it is likely to index cognitive control mechanisms that may be recruited for bilinguals' linguistic competition resolution.

We predicted that a link would exist between Stroop performance and parallel language activation during auditory word identification and that this association would be mediated by language proficiency. To examine whether bilingual proficiency simultaneously influences parallel language activation and cognitive control, bilingual participants were divided into higher-proficiency and lower-proficiency groups. Increased bilingual proficiency has been associated with both, more robust parallel language activation (e.g., Blumenfeld & Marian, 2007) as well as more efficient cognitive control skills (e.g., Singh & Mishra, 2007). This leads to a dual prediction about crosslinguistic activation as proficiency increases. First, parallel language activation is predicted to become more robust as nontarget representations are coactivated more automatically. Second, crosslinguistic interference is predicted to be resolved more efficiently as cognitive control skills improve. We can situate these seemingly contradictory predictions within models of bilingual receptive processing in highly interactive architectures (BIA, Dijkstra & van Heuven, 2002, and van Heuven, Dijkstra, & Grainger, 1998; BLINCS, Shook & Marian, 2013). Both the BIA and BLINCS posit bottom-up parallel language activation as well as the subsequent action of higher-level cognitive control mechanisms to guide word selection. According to these theoretical frameworks and previous literature, more robust parallel language activation and better inhibitory control may both be associated with higher proficiency, but the two effects are likely exerted at different points in the time course of word recognition. The present study explicitly tests this hypothesis, and juxtaposes the two predictions by examining the relationship between language activation and inhibitory control across the time course of coactivation and deactivation. First, given previous findings that

higher bilingual proficiency is related to increased parallel language activation and to better cognitive control (Blumenfeld & Marian, 2007; Singh & Mishra, 2007), we examined whether greater parallel activation would be associated with better Stroop performance during *early* stages of word recognition. Second, since better cognitive control has also been linked to less crosslinguistic activation (Gollan et al., 2011; Linck et al., 2008), we expected better Stroop performance to be associated with less crosslinguistic activation during a *later* competition resolution stage where inhibitory control would be applied.

In sum, we predicted that higher-proficiency bilinguals would show stronger parallel language activation (e.g., Blumenfeld & Marian, 2007; Ju & Luce, 2004), suggesting more automatized access to robust representations, and smaller Stroop effects (e.g., Singh & Mishra, 2012), indicating honed abilities in inhibitory control. Moreover, across all bilinguals, we predicted that correlational relationships would emerge between parallel language activation and Stroop performance. Specifically, we predicted that higher-proficiency bilinguals would show initial coactivation of crosslinguistic competitors, followed by efficient resolution of such competition as a function of inhibition skills.

METHOD

Participants

Thirty-one English-Spanish bilinguals (9 males, mean age = 22.0, $SD = 5.1$) and 30 English monolinguals (6 males, mean age = 21.4, $SD = 3.9$) participated.¹ Bilinguals were divided into a group with higher Spanish proficiency ($n = 15$) and a group with lower Spanish proficiency ($n = 16$) based on their Spanish verbal fluency performance (letters and categories combined) and using a median-split procedure. Higher Spanish proficiency bilinguals outperformed lower Spanish proficiency bilinguals on Spanish verbal fluency across letters and categories, $t(29) = 6.7$, $p < .001$ (see Table 1 for linguistic and cognitive background characteristics of the 2 bilingual

¹Thirty monolinguals were recruited to ensure that null findings in monolinguals' correlations between eyetracking and cognitive control measures were not due to a lack of power.

TABLE 1

Linguistic and cognitive background characteristics for higher-proficiency and lower-proficiency bilinguals, including number of correct words produced on Spanish verbal fluency tasks

	Higher-proficiency bilinguals Mean (SE)	Lower-proficiency bilinguals Mean (SE)
Age of Spanish acquisition ^{ns}	2.1 (.7)	2.9 (.8)
Current exposure to Spanish ^{ns} (%)	25.9 (3.7)	18.4 (3.6)
Digit span ^{ns}	17.5 (.6)	17.8 (.7)
WASI, matrix reasoning ^{ns}	109.3 (2.6)	110.6 (2.9)
English receptive vocabulary ^{ns}	117.7 (3.3)	114.9 (2.9)
Self-reported Spanish proficiency* (1–10 scale)	8.1 (.3)	7.3 (.3)
Spanish letter fluency**	12.3 (.5)	7.1 (.3)
Letter E	11.3 (.8)	5.6 (.8)
Letter P	12.3 (.4)	7.7 (.8)
Letter M	12.4 (.8)	6.7 (.4)
Letter A	12.5 (2.7)	6.8 (.7)
Letter L	12.0 (1.7)	6.8 (.4)
Letter C	15.0 (.7)	8.9 (.9)
Spanish category fluency**	10.1 (.9)	7.0 (.6)
ANIMAL category (<i>Animales</i>)	15.4 (2.3)	8.2 (1.1)
FRUITS category (<i>Frutas</i>)	10.0 (1.9)	5.9 (1.1)
CLOTHES category (<i>Vestidos</i>)	10.2 (2.2)	6.2 (1.1)
COLORS category (<i>Colores</i>)	12.0 (.8)	11.0 (1.0)
VEGETABLES category (<i>Verduras</i>)	6.3 (1.0)	3.6 (.9)
Overall Spanish verbal fluency**	11.4 (.6)	7.0 (.6)

**Between-group differences at $p < .01$; *between-group difference at $p < .05$; ^{ns} = not significant.

groups). In addition, the higher-proficiency group self-reported higher Spanish proficiency than the lower-proficiency group, $t(29) = 2.1$, $p < .05$. The 2 bilingual groups did not differ in age of Spanish acquisition, $t(29) = .8$, $p > .1$, or in their current exposure to Spanish, $t(29) = .9$, $p > .1$. The monolingual group and the 2 bilingual groups did not differ in age at the time of testing, $F(2, 58) = 3.1$, $p > .05$, (monolinguals: $M = 21.4$, $SE = .7$; lower-proficiency bilinguals: $M = 20.3$, $SE = .7$; higher-proficiency bilinguals: $M = 24.0$, $SE = 1.6$), performance on the nonverbal portion of the Wechsler Abbreviated Scale of Intelligence, $F(2, 58) = .1$, $p > .5$ (monolinguals: $M = 110.5$, $SE = 2.2$; lower-proficiency bilinguals: $M = 110.6$, $SE =$

2.9; higher-proficiency bilinguals: $M = 109.3$, $SE = 2.6$), digit span, $F(2, 58) = .5$, $p > .5$ (monolinguals: $M = 17.5$, $SE = .4$; lower-proficiency bilinguals, $M = 17.8$, $SE = .7$; higher-proficiency bilinguals, $M = 17.5$, $SE = .6$), or receptive vocabulary in English: Peabody Picture Vocabulary Test: $F(2, 58) = .2$, $p > .5$ (monolinguals: $M = 116.7$, $SE = 2.1$; lower-proficiency bilinguals: $M = 114.9$, $SE = 2.9$; higher-proficiency bilinguals: $M = 117.7$, $SE = 3.3$).

Design

The eyetracking component of the current study followed a 2×3 design, with fixations on pictures of crosslinguistic competitors relative to pictures of unrelated filler items as a within-subject variable and with membership in the higher-proficient bilingual group, the lower-proficient bilingual group or the monolingual group as a between-subjects variable. Similarly, the nonlinguistic Stroop component of the study followed a 2×3 design, with responses to trials with perceptually competing information (e.g., a left-pointing arrow on the right side), compared to trials without competing information (e.g., a left-pointing arrow on the left side), as a within-subject variable, and with group as a between-subjects variable. Finally, to examine the relationship between parallel language activation and cognitive control, a correlational design was employed where the extent of parallel language activation was correlated with nonlinguistic Stroop performance across participants and across the time course of language activation. Dependent variables included accuracy and latency of responses, as well as fixations on images during eyetracking.

Stimuli

Crosslinguistic coactivation during word recognition

To index crosslinguistic competition, a word recognition eyetracking paradigm was used. In addition to auditory targets, displays contained pictures of *between-language* competitors. For example, participants heard the word *pool*, while a picture of a thumb (Spanish *pulgar*) was also present (see Figure 1A). Phonological overlap between English targets and Spanish competitors was high, including at least 2 shared word-initial

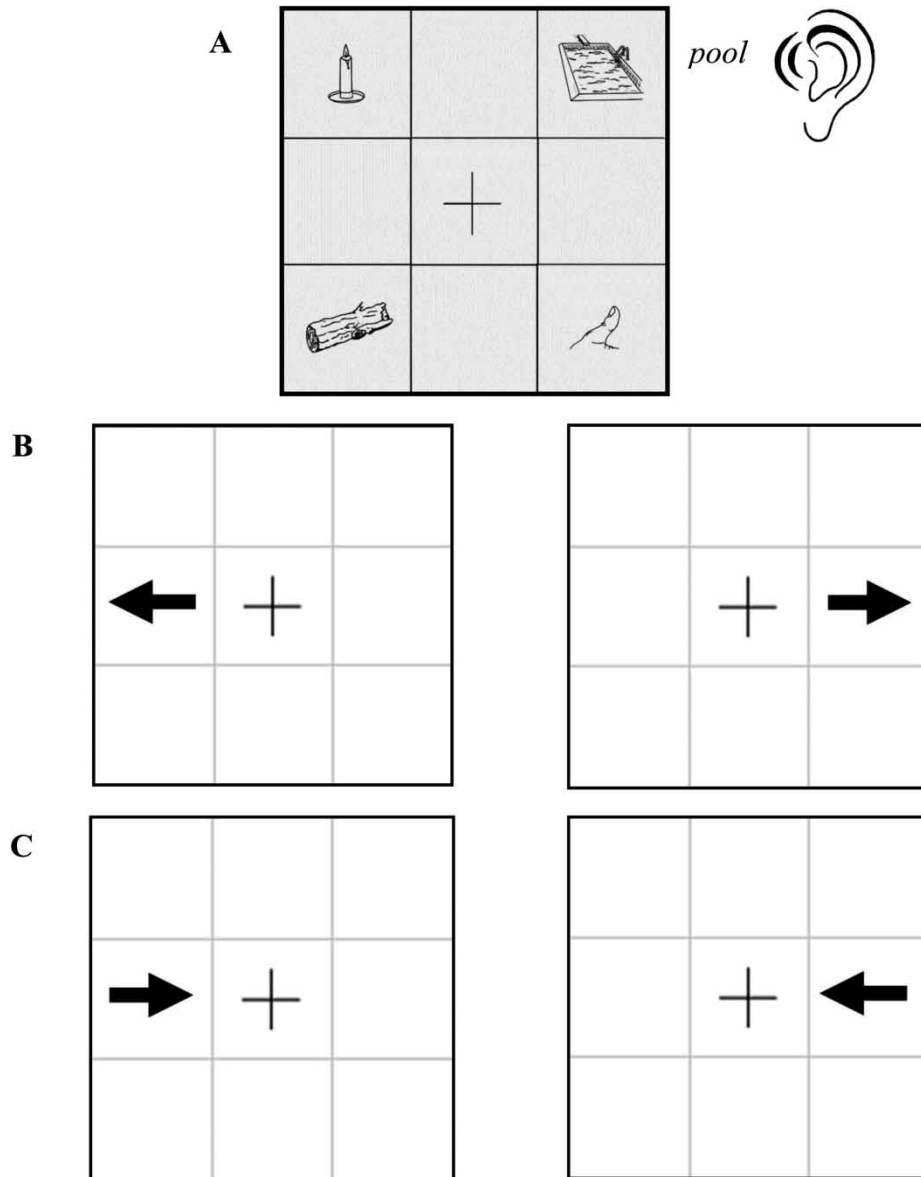


Figure 1. Stimulus displays for the auditory word recognition task (A: participants heard *pool* in the presence of the crosslinguistic competitor *pulgar*, “thumb” in Spanish) and the nonlinguistic spatial Stroop task (B: congruent condition where arrow location and direction match; C: incongruent condition where arrow location and direction mismatch).

phonemes. Crosslinguistic phonological overlap was also measured in terms of duration of acoustic overlap, and averaged 251.1 ms ($SE = 31.1$) across target–competitor pairs. Recordings were made in a sound-proof booth (44,100 Hz, 16 bits) by a female native speaker of English, using a Marantz Solid State recorder (PMD670). Normalisation, segmentation, and phonological overlap analyses of sound files were performed using Praat and Sound Studio software. The resulting sound files were then imported into Superlab experimental software. During the experimental

session, the name of the target picture was presented 500 ms after the onset of the picture display, consistent with previous eyetracking studies (e.g., Ju & Luce, 2004; Weber & Cutler, 2004). Stimulus trials were separated by 500 ms intertrial intervals and picture target identification was self-paced, with picture displays disappearing once a response was made.

Stimuli for the crosslinguistic competition task consisted of 20 trials that included crosslinguistic competitors, as well as 40 filler trials where no competitor image was present. The ratio of

competitor trials to filler trials was 1:2 in order to minimise awareness of phonological overlap, and to maximise competition effects (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Green, 1998; Henik, Bibi, Yanai, & Tzelgov, 1997). Some of the target–competitor pairs were adapted from Ju and Luce (2004) and from Canseco-Gonzalez et al. (2010). Because Dahan, Magnusson, and Tanenhaus (2001) found that competitor pictures with a word frequency higher than that of the target picture competed with targets most strongly, we controlled the frequencies of our crosslinguistic competitors so that they were similar to English target word frequencies. Spoken word frequencies were obtained in English for the target stimuli (Celex lexical database; Baayen, Piepenbrock, & van Rijn, 1995) and in Spanish for the competitor stimuli (Corpus del Español, www.corpusdelespanol.com). Frequencies, in words per million, were statistically equivalent for English targets ($M = 20.1$, $SE = 5.4$) and Spanish competitors ($M = 41.1$, $SE = 14.0$), $t(32) = 1.5$, $p > .1$. For a list of stimuli, see the Appendix.

Stimulus displays consisted of four pictures and a central fixation cross. The four pictures in each display consisted of (1) the target word, (2) a Spanish competitor word in critical trials and a filler word in filler trials, and (3, 4) two additional filler items. Pictures consisted of black line drawings on a light grey background. Images were obtained from the International Picture Naming Database (Székely et al., 2004), the IMSI Master Clips database, and a previous study (Blumenfeld & Marian, 2007), and were adjusted for line thickness and salience within each display using Photoshop. Each stimulus picture was approximately 5×5 cm in size, and the centre of each individual picture was located 13 cm away from the central fixation cross in the middle of the display. One purpose of the monolingual control group was to ensure that findings were not influenced by differences in visual salience across stimulus displays, with an equal proportion of looks expected to competitors and fillers for monolinguals.

Nonlinguistic Stroop task

The nonlinguistic Stroop task employed in the present study was also used in Blumenfeld and Marian (2011). Participants were asked to respond to arrow direction (either right or left) but to ignore the location of the arrow on the

display (either right or left) (see Figure 1B–C). These 2 stimulus dimensions were manipulated to be either congruent or incongruent.² Participants were instructed to press a response-key located on the *left* side of the keyboard when they saw a *leftward*-facing arrow, and a response-key on the *right* when they saw a *rightward*-facing arrow. The congruent trials consisted of 60 trials that contained a leftward-facing arrow presented to the left of the central fixation cross, and 60 trials that contained a rightward-facing arrow presented to the right of the central fixation cross. The incongruent trials consisted of 20 trials that contained a *leftward*-facing arrow presented to the *right* of the central fixation cross, and 20 trials that contained a *rightward*-facing arrow presented to the *left* of the central fixation cross. Each trial started with a 500 ms central fixation cross, followed by a 700 ms presentation of the stimulus display, and an 800 ms presentation of a blank screen. Trials were presented in a fixed pseudorandomised order.

Procedures and apparatus

After informed consent was obtained, participants completed the eyetracking part of the study. Participants were not aware of a Spanish component to the task and, prior to completing the English-Spanish eyetracking task, had been exposed to only English in the laboratory. During a practice session, participants were trained to identify the quadrant containing the correct stimulus target, by pressing 1 of 4 keys that were marked on the test computer's keyboard. These keys corresponded spatially to the location of the quadrant on the stimulus display. Specifically, participants pressed an upper left key to identify a stimulus in the upper left quadrant, an upper right key to identify a stimulus in the upper right quadrant, a bottom left key to identify a stimulus in the bottom left quadrant, and a

²The spatial Stroop task in the current study consisted of only congruent and incongruent trials, consistent with Liu et al. (2004) and with Blumenfeld and Marian (2011). In this study, we aimed to establish an initial link between parallel language activation and a cognitive task that has been shown to have neural correlates (Liu et al., 2004) consistent with those of cognitive control processes in bilinguals (Abutalebi, 2008; Liu et al., 2004). We reasoned that, if participants can inhibit irrelevant location information, then incongruent location information should interfere less with their response and congruent location information should provide less facilitation towards their response, thus providing a reduced difference score between congruent and incongruent conditions.

bottom right key to identify a stimulus in the bottom right quadrant. Participants practised making responses using the spatially corresponding keys and without looking at the keyboard on 60 practice trials where they were asked to identify a nonlinguistic symbol in different quadrants. After task instructions and practice, participants were calibrated on the headmounted (ISCAN) eyetracking system. A scene camera captured participants' field of view, and an infrared camera allowed the software to track the pupil and corneal reflection. Gaze position was indicated by cross-hairs superimposed over the image generated by the scene camera, and participants' eye movements were calibrated to 9 points on the computer screen (G4 Macintosh, 27 × 34 cm).

Following eyetracking, participants completed the nonlinguistic Stroop task and the verbal fluency tasks in English and Spanish. In the fluency tasks, letter sets E, P, M, A, L, and C and category sets Animals, Fruits, Clothes, Colours, and Vegetables were counterbalanced across participants and languages, and standard procedures were followed in administration and coding of the task (e.g., Gollan, Montoya, & Werner, 2002). We chose verbal fluency, a generative production measure, as an index of proficiency since it poses greater retrieval challenges than a receptive task, and is thus a better indicator of the robustness of lexical knowledge. Bilingual disadvantages have been identified in category fluency tasks, and these tasks have been accepted as a good measure of lexical knowledge (e.g., Gollan et al., 2002). Lexical knowledge is also a prerequisite to high performance on letter fluency tasks (Gollan et al., 2002; Luo, Luk, & Bialystok, 2010). Participants were median-split into higher- and lower-proficiency groups based on this measure in order to examine parallel language activation and cognitive control skills separately for groups with higher and lower Spanish word retrieval skills. Participants were also administered the nonverbal components of the Wechsler Abbreviated Scale of Intelligence (WASI; PsychCorp, 1999) as a measure of nonverbal cognitive reasoning, as well as the Peabody Picture Vocabulary Task (PPVT; Dunn & Dunn, 1997), which indexes English receptive vocabulary required in the word recognition task, and a digit span task to account for short-term memory (Comprehensive Test of Phonological Processing; Wagner, Torgesen, & Rashotte, 1999), a cognitive skill that has been shown to influence word

retrieval in bilinguals (Kaushanskaya et al., 2011). Finally, participants completed the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007).

Coding and analyses

For both the critical trials on the eyetracking task and for the nonlinguistic Stroop task, accuracy rates and reaction times were analysed, and instances of incorrect picture identification or response latencies beyond 2.5 standard deviations from the mean were excluded from further analyses. In the auditory word recognition task, both by-subject and by-item analyses were performed; in the Stroop task, only by-subject analyses were performed as all items were identical within-condition. The video output from eyetracking had a temporal resolution of 33.3 ms per frame, and was manually coded using Final Cut Pro software. Eye movements to pictures were coded as fixations if they entered the picture's quadrant and remained there for at least 1 frame. Starting at the onset of the stimulus word, and across the time course of lexical activation, fixations on the target, competitor, or filler images were counted as "1"s and eye movements outside of the 4 areas of interest were coded as "0"s. Data for 20 crosslinguistic trials were collected. Three items were excluded from analyses because, upon closer inspection, they included within-language phonological overlap in addition to between-language overlap.³ The remaining 17 trials were included in eyetracking analyses. Fifteen per cent of all eyetracking data were recoded by a second trained coder, and point-to-point interrater reliability was .93 (pairwise Pearson r , $p < .001$). Since it takes approximately 200 ms to plan an eye movement (Hallett, 1986), time course analyses focused on activation beyond the initial 200 ms post word onset. Activation curves between 0 and 2600 ms post word onset were inspected visually, and looks between 200 ms and 1100 ms post word onset

³The 3 target-competitor pairs that were omitted because of within-language overlap were (1) target *seal* and Spanish competitor *silla* ("chair") due to the English synonym *seat*; (2) target *beans* and Spanish competitor *bigote* ("moustache") due to the English word *beard*; and (3) target *female* and Spanish competitor *fiesta* ("party") due to the English word *feast* and because monolingual participants were likely familiar with the word *fiesta*.

(when looks to targets had reached a maximum) were analysed statistically. This approach to analysis of eyetracking data is consistent with previous approaches (e.g., Blumenfeld & Marian, 2007, 2011; Weber & Cutler, 2004). Finally, to examine how individual differences in inhibitory control may relate to the extent of parallel language activation and how this relationship changes across the time course of word recognition, correlations were conducted between Stroop effects (incongruent minus congruent trials) and parallel language activation (looks to competitors minus looks to fillers) for each 33 ms time frame during the parallel language activation window (see Costa, Strijkers, Martin, & Thierry, 2009, for a similar approach with ERP data and behavioural reaction times during naming). We reasoned that, if cognitive control mechanisms were recruited for competition resolution, then correlations between Stroop performance and parallel language activation should be present across multiple adjacent time frames. For the analysis of time series with high autocorrelation, Guthrie and Buchwald (1991) conducted simulations and generated statistical significance thresholds ($p < .05$) for the probability of finding a series of significant tests in adjacent time windows. We compared our findings against these thresholds to correct for multiple comparisons in correlation analyses. Sporadic correlations in single time frames were treated as chance events for the previously stated theoretical and statistical reasons.

RESULTS

Parallel language activation and bilingual proficiency

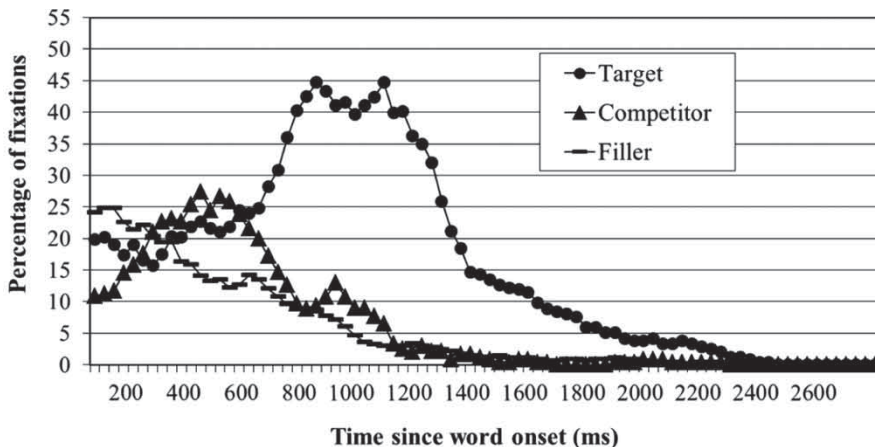
Accuracy and reaction time analyses on critical picture identification trials yielded similar performance for monolinguals (accuracy: $M = 99.4\%$, $SE = .3$; reaction times: $M = 1622.7$ ms, $SE = 25.6$), higher-proficiency bilinguals (accuracy: $M = 99.3\%$, $SE = .5$; reaction times: $M = 1719.3$ ms, $SE = 59.7$), and lower-proficiency bilinguals (accuracy: $M = 97.8\%$, $SE = .8$, $F_1(2, 58) = 2.8$, $p = .07$, $F_2(2, 48) = 2.2$, $p > .1$; reaction times: $M = 1708.4$ ms, $SE = 64.3$, $F_1(2, 58) = 1.6$, $p > .1$, $F_2(2, 48) = 1.4$, $p > .1$). Analyses on the extent of parallel language activation in higher-proficiency and lower-proficiency bilinguals relative to monolinguals during the 200–1100 ms time win-

dow were performed using a 2×3 ANOVA, with fixation type (competitor, filler) as a within-subject variable and group (higher-proficiency bilingual, lower-proficiency bilingual, monolingual) as a between-subjects variable. Results revealed a main effect of fixation type, $F_1(1, 58) = 15.7$, $p < .001$, $\eta_p^2 = .2$, $F_2(2, 48) = 7.4$, $p < .01$, $\eta_p^2 = .1$, and a by-subjects interaction between fixation type and group, $F_1(2, 58) = 3.3$, $p < .05$, $\eta_p^2 = .1$, $F_2(2, 58) = 1.7$, $p = .2$, $\eta_p^2 = .1$ (see Figure 2 and Table 2). Specifically, planned follow-up analyses showed that higher-proficiency bilinguals were more likely to look at cross-linguistic competitors compared to fillers, $t_1(14) = 3.6$, $p < .01$, $t_2(16) = 2.5$, $p < .05$, with equal percentages of looks to competitors and fillers for lower-proficiency bilinguals, $t_1(15) = 1.2$, $p > .1$, $t_2(16) = .7$, $p > .1$, and for monolinguals, $t_1(29) = 1.6$, $p > .1$, $t_2(16) = 1.6$, $p > .1$.

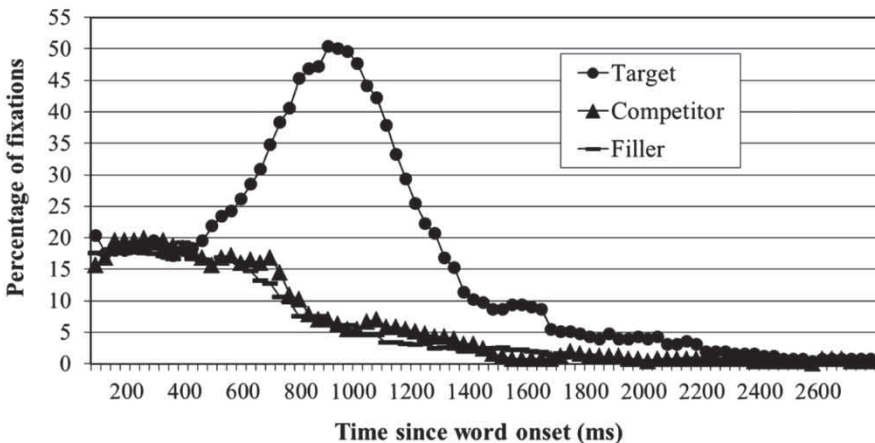
Parallel language activation, language proficiency, and inhibitory control

To examine whether bilingual proficiency and parallel language activation can be directly linked to cognitive control, participants' eyetracking results were examined relative to their performance on the nonlinguistic Stroop task. Accuracy rates and reaction times during Stroop performance were entered into a 2×3 ANOVA, with trial type (incongruent, congruent) as a within-subject variable and group (higher-proficiency bilinguals, lower-proficiency bilinguals, monolinguals) as a between-subjects variable. For accuracy rates, a main effect of trial type was identified, $F(1, 58) = 81.0$, $p < .001$, $\eta_p^2 = .6$, with overall less accurate performance on incongruent trials ($M = 85.0\%$, $SE = 1.6$) than on congruent trials ($M = 91.1\%$, $SE = .4$), see Table 3. No interaction between trial type and group and no main effect of group were found ($ps > .1$). Reaction time analyses yielded a main effect of trial type, $F(1, 58) = 498.4$, $p < .001$, $\eta_p^2 = .9$, no main effect of group, $F(2, 58) = .05$, $p > .5$, and an interaction between trial type and group, $F(2, 58) = 5.8$, $p < .01$, $\eta_p^2 = .2$, suggesting slower responses on incongruent ($M = 457.0$ ms, $SE = 7.4$) than on congruent ($M = 370.4$ ms, $SE = 6.4$) trials (see Figure 3). Follow-up comparisons of Stroop effects (incongruent trials minus congruent trials) across groups suggested that higher-proficiency bilinguals had smaller Stroop effects ($M = 66.9$ ms, $SE = 5.7$)

A. HIGHER-PROFICIENCY BILINGUALS



B. LOWER-PROFICIENCY BILINGUALS



C. MONOLINGUALS

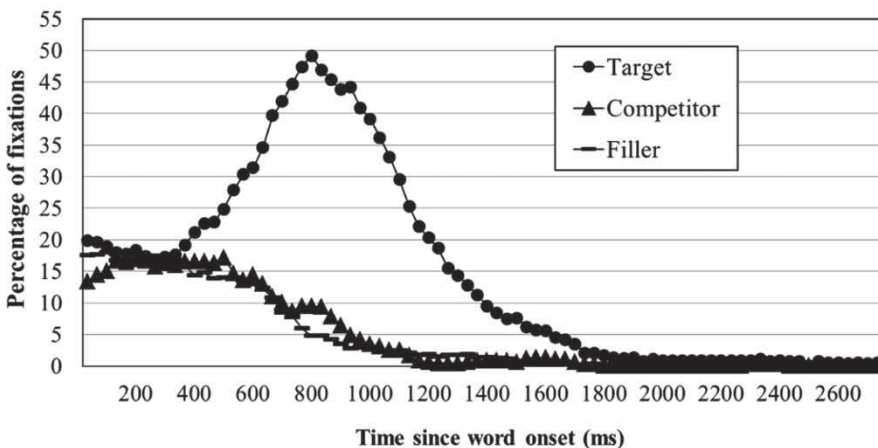


Figure 2. Time course of language activation as indexed by eyetracking in bilinguals who were highly proficient in Spanish (A), bilinguals who were less proficient in Spanish (B), and monolinguals (C).

than lower-proficiency bilinguals ($M = 99.5$ ms, $SE = 7.2$), $t(29) = 3.5$, $p = .001$, or monolinguals ($M = 93.6$ ms, $SE = 5.8$), $t(43) = 4.3$, $p < .01$. The

Stroop effects were statistically equivalent in lower-proficiency bilinguals and monolinguals, $t(44) = .6$, $p > .5$. These findings suggest that nontarget

TABLE 2

Percentage of fixations on competitor and filler pictures between 200 and 1100 ms after the onset of the auditory target word for higher-proficiency bilinguals, lower-proficiency bilinguals, and monolinguals

	Competitor pictures % (SE)	Filler pictures % (SE)	Competition effect (competitor – filler)
Higher-proficiency bilinguals	15.8 (1.1)	11.0 (.5)	4.8*
Lower-proficiency bilinguals	12.5 (.9)	11.3 (.8)	1.2%
Monolinguals	11.2 (.9)	9.8 (.7)	1.4%

* $p < .01$.

language proficiency mediated both the extent of parallel language activation and the ability to inhibit competing information in the nonlinguistic domain, with bilinguals who showed greater parallel language activation also showing reduced nonlinguistic Stroop effects.

To examine the link between parallel language activation and inhibitory control abilities, correlations were performed between the two across the window where parallel language activation was present (between 200 and 833 ms, resulting in comparisons across 20 time frames). In higher and lower proficiency *bilingual* participants combined, parallel language activation effects (competitor fixations minus filler fixations) were correlated with Stroop effects (incongruent trials minus congruent trials). Significant *negative* correlation coefficients were identified between 300 and 500 ms

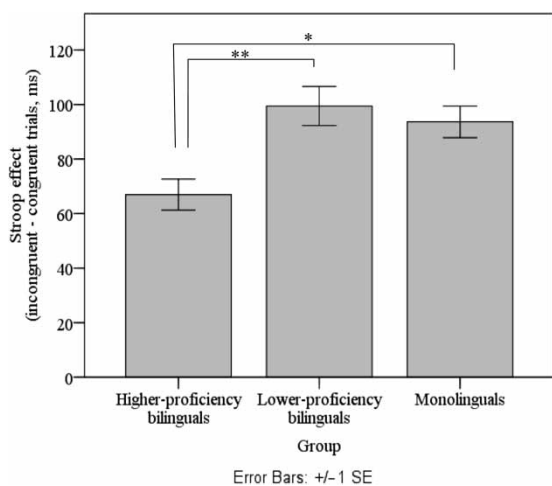


Figure 3. Stroop performance on congruent and incongruent trials in higher- and lower-proficiency bilinguals and monolinguals.

post word onset, $r = -.5$, $p = .01$, 95% confidence interval for $r = -.3$ to $-.6$. In addition, significant *positive* correlation coefficients were identified between 633 and 767 ms post word onset, $r = .4$, $p < .05$, 95% confidence interval for $r = .1$ to $.6$. Notably, the negative correlations between 300 and 500 ms corresponded to the time course of competitor activation (increased differences between competitor vs. filler fixations), whereas the positive correlations between 633 and 767 ms corresponded to competitor *deactivation* (reduced differences between competitor versus filler fixations, see Figure 4A, open triangles). These findings are consistent with our expectations of multiple consecutive significant correlations across the course of parallel activation. Both windows where consecutive significant correlations were present passed the threshold of significance within a 10-frame sequence where autocorrelation (lag 1) = .9, $p < .05$ (Guthrie & Buchwald, 1991). A Fisher *r*-to-*z* transformation suggested that the 2 correlation coefficients were significantly different from each other, $z = 3.3$, $p < .001$. This pattern suggests that bilinguals who showed *strong* parallel language activation between 300 and 500 ms and *reduced* parallel language activation between 633 and 767 ms also showed *smaller* Stroop effects (see Figure 4B–C). To examine whether similar patterns were present in higher- and lower-proficiency bilinguals, correlation analyses between Stroop performance and parallel language activation were also performed for each group separately. Patterns towards negative correlations were identified in the 300–500 ms time window for both higher-proficiency, $r = -.4$, $p = .1$, and lower-proficiency groups, $r = -.4$, $p = .2$, and significant positive correlations were found in the 633–767 ms time window for both higher-proficiency, $r = .5$, $p < .05$, and lower-proficiency groups, $r = .6$, $p = .01$. When the same correlation analyses were conducted in the monolingual control group, only temporary (1 frame in terms of the eyetracking sampling rate) and inconsistent *positive* correlations were found at 200–233 ms, at 400–433 ms, and at 467–500 ms (all $ps < .05$). It is possible that these correlations were driven by monolinguals who performed well on the Stroop task and made overall fewer looks to *any* nontarget items. However, their temporary nature suggests that no consistent pattern was present in the monolingual data linking eye movements during comprehension to Stroop inhibition.

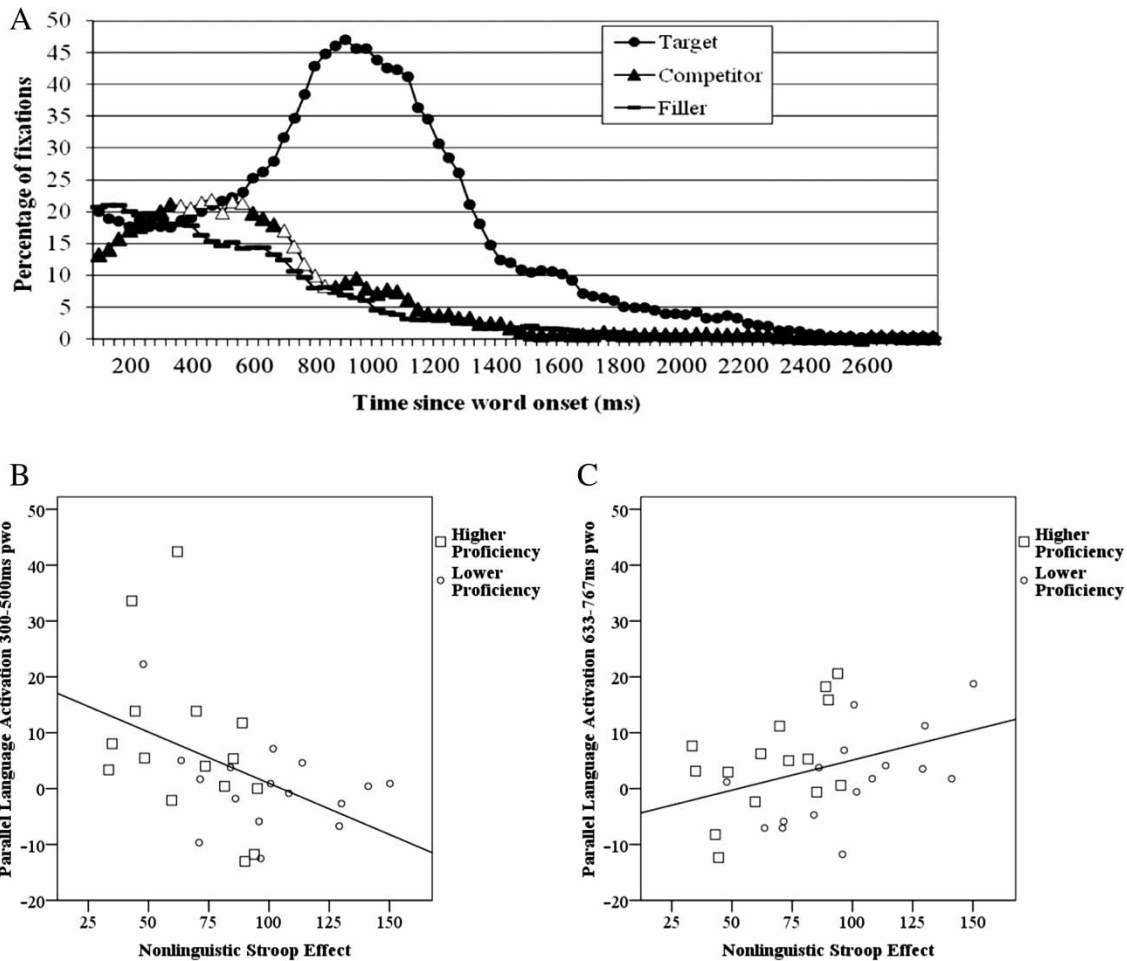
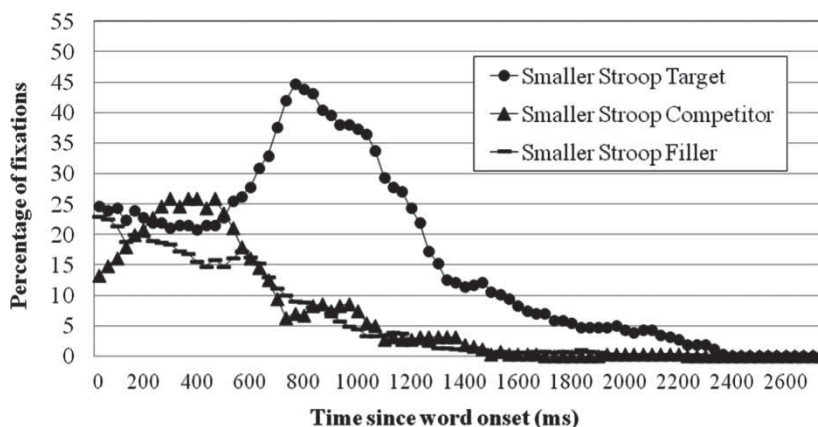


Figure 4. Time course of language activation as indexed by eyetracking across *all* bilinguals, with significant correlations between parallel activation and Stroop performance marked with open triangles (A), and correlations between parallel activation (competitor minus filler fixations) and Stroop performance (incongruent minus congruent trials) 300–500 ms post word onset (B, $r = -.5, p = .01$); and 633–767 ms post word onset (C, $r = .4, p < .05$).

To more closely examine how Stroop performance influences the time course of parallel language activation, bilinguals were median-split into individuals with smaller Stroop effects ($M = 59.2$ ms, $SE = 4.2$) and larger Stroop effects ($M = 106.7$ ms, $SE = 5.1$), $t(29) = 7.1, p < .001$. The bilinguals with smaller Stroop effects looked to competitors ($M = 25.5\%$, $SE = 2.7$) significantly more frequently than to fillers ($M = 15.5\%$, $SE = 1.4$) between 300 and 500 ms post stimulus onset (see Figure 5A), $t_1(14) = 2.7, p < .05, t_2(16) = 1.2, p > .1$. The bilinguals with larger Stroop effects looked to competitors ($M = 15.3\%$, $SE = 1.4$) significantly more frequently than to fillers ($M = 9.4\%$, $SE = 1.0$) between 567 and 833 ms post stimulus onset (see Figure 5B), $t_1(15) = 3.3, p < .01, t_2(16) = 2.3, p < .05$. A $2 \times 2 \times 2$ ANOVA

with stimulus type (competitor, filler) and time window (300–500 ms, 567–833 ms) as within-subject variables and with group (bilinguals with smaller Stroop effects, bilinguals with larger Stroop effects) as a between-subjects variable yielded a significant 3-way interaction, suggesting that the 2 groups differed significantly in the time course of parallel language activation, $F_1(1, 29) = 15.4, p < .001, \eta_p^2 = .4, F_2(1, 32) = 6.5, p < .05, \eta_p^2 = .2$. These findings suggest that differences in the time course of activation across groups with smaller versus larger Stroop effects may contribute to correlations between parallel language activation and Stroop performance. Together, correlation analyses between parallel language activation and Stroop performance suggest that bilinguals showed a close and continuous relationship

A. BILINGUALS WITH SMALLER STROOP EFFECTS



B. BILINGUALS WITH LARGER STROOP EFFECTS

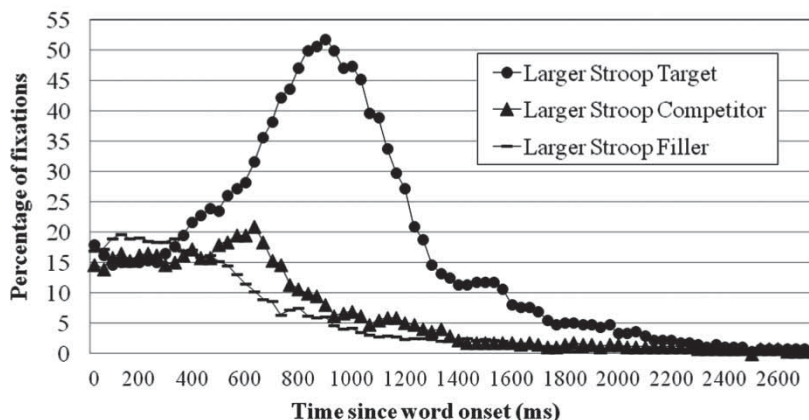


Figure 5. Time course of language activation as indexed by eyetracking across bilinguals who demonstrated smaller Stroop effects (A) and bilinguals who demonstrated larger Stroop effects (B).

between the 2 processes, and that the nature of this relationship changed across the time course of competitor activation.

DISCUSSION

In the current study, we examined whether parallel language activation during auditory word recognition is directly related to bilingual advantages in inhibitory control. Using a cross-linguistic visual world eyetracking task and a nonlinguistic Stroop task, we identified a link between parallel language activation and Stroop performance, with higher-proficiency bilinguals showing stronger parallel language activation *and* cognitive advantages in the form of smaller Stroop effects. Moreover, across all bilinguals, correlational relationships emerged between parallel language activation and Stroop performance.

Higher bilingual proficiency and better Stroop performance were associated with higher cross-linguistic activation during word recognition *early* in the time course (300–500 ms post word onset). During a *later* time window (633–767 ms post word onset), better Stroop performance became associated with less parallel language activation. Bilinguals with better Stroop performance showed deactivation of competitors during this later time window, whereas bilinguals with less efficient Stroop performance showed competitor activation. These findings suggest a dynamic relationship between crosslinguistic activation and cognitive control, where better Stroop inhibition abilities are associated with early competitor activation.

The present findings suggest that the nature of the relationship between parallel language activation and Stroop inhibition changes across time. These findings can be interpreted within the

framework of models of bilingual receptive processing, such as the Bilingual Language Interaction Network for Comprehension of Speech (BLINCS; Shook & Marian, 2013) or the Bilingual Interactive Activation model (BIA; Dijkstra & van Heuven, 2002; van Heuven et al., 1998). In these models, early stages of comprehension are characterised by automatic and parallel bottom-up activation of representations. Following this initial parallel activation process, higher-level cognitive control mechanisms are available to guide word selection. Our findings fit well with the 2 stages exemplified by the BIA and BLINCS, with higher-proficiency bilinguals showing strong parallel activation during early word recognition (300–500 ms post word onset) and recruitment of cognitive control mechanisms to resolve competition later on.

It should be noted that studies linking better inhibition to less crosslinguistic activation have used production tasks that rely on response output measures (e.g., naming, Gollan et al., 2011; Linck et al., 2008), thus indexing performance at a later stage where inhibitory control would likely have already been applied to resolve competition. In contrast, the present study employed an online word recognition task that targeted early stages of comprehension where activation was automatic. Therefore, the present study captures both automatic crosslinguistic activation *and* competition resolution stages during the time course of word recognition.

The role of proficiency and cognitive control across the time course of auditory word recognition

The findings of the present study suggest that the relationship between parallel language activation and Stroop performance is likely to change over the time course of word recognition. Although the current study cannot make claims about the direction of the relationship between proficiency, parallel language activation, and Stroop performance, cognitive control and parallel activation are likely to mutually influence each other as bilingual proficiency is developed. One possible progression in the development of the patterns identified in the current study is that (1) the nontarget language must reach a certain proficiency level before it becomes routinely and automatically coactivated; (2) the need to resolve crosslinguistic competition due to parallel activa-

tion may engage and hone cognitive control mechanisms; and finally, (3) as cognitive control mechanisms become more efficient, associated nonlinguistic and linguistic competition resolution becomes more efficient. In addition, it is likely that preexisting individual differences in bilinguals' inhibitory control contribute to competition resolution. For example, previous studies have suggested that *increased* crosslinguistic activation can be linked to *reduced* inhibitory control abilities (Gollan et al., 2011; Linck et al., 2008), suggesting that although crosslinguistic competition may hone inhibitory control, proficient bilinguals with weaker cognitive control mechanisms will nevertheless experience more crosslinguistic interference.

Results identified in the present study map onto the hypothesised progression of high bilingual proficiency, crosslinguistic competition, and honed cognitive control/linguistic conflict resolution: First, bilinguals who showed higher proficiency in the nontarget language also showed increased parallel language activation (for similar findings, see Blumenfeld & Marian, 2007). Second, bilinguals with better Stroop performance also showed more parallel language activation early during word recognition (negative correlation between 300 and 500 ms post word onset), supporting the hypothesis that the presence of crosslinguistic competition hones aspects of cognitive control. It is possible that the time course differences in competitor activation that were identified for bilinguals with smaller versus larger Stroop effects are mediated by language proficiency. For example, Blumenfeld and Marian (2007, cognate condition) showed coactivation of German competitors earlier in the activation time course for German-English bilinguals than for English-German bilinguals. Similarly, Dahan et al. (2001) showed earlier activation of higher-frequency words. In this sense, the negative correlation between 300 and 500 ms may reflect *identification* of individuals who show the most immediate and automatised parallel language activation, a precondition of high crosslinguistic competition and of potential benefits to cognitive performance. Conversely, the positive correlation between 633 and 767 ms may reflect actual *engagement* of cognitive control mechanisms, since less parallel language activation corresponds to better Stroop performance during this time period. This explanation is consistent with current research on the emergence of bilingual cognitive advantages (e.g., Bialystok & Craik, 2010; Green,

2011; Kroll, 2008); future studies may further examine the development of the identified relationships between language activation and Stroop performance.

Parallel language activation as a source of a bilingual cognitive advantage

Regardless of the specific explanation of correlations between Stroop performance and parallel activation across the time course of performance, the present findings suggest that, when bilinguals were divided into higher-proficiency and lower-proficiency speakers in the nontarget language (L2), the higher-proficiency group showed more parallel language activation and better Stroop performance. These differences between higher and lower Spanish proficiency groups were observed despite similarity in the 2 groups on nonverbal IQ, digit span performance, and English proficiency. Moreover, a direct relationship was established between Stroop performance and parallel language activation across 2 continuous time windows during auditory word identification. These findings support the prediction that bilingual parallel language activation can indeed be directly and systematically linked to the involvement of cognitive control mechanisms. Crucially, bilingual parallel language activation was linked to Stroop performance, a type of inhibitory control that has repeatedly yielded advantages in bilinguals compared to monolinguals (e.g., Bialystok, 2006; Bialystok et al., 2008; Bialystok & DePape, 2009; Costa et al., 2008; Costa, Hernandez et al., 2009; Hernández et al., 2010; Luk et al., 2011) and that has been shown to rely on different neural pathways in bilinguals versus monolinguals (Luk et al., 2010), suggesting its modulation with bilingual experience. In fact, in the current study, higher-proficiency bilinguals showed advantages on the nonlinguistic Stroop task relative to lower-proficiency bilinguals and monolinguals.

Finding a Stroop inhibition advantage only in higher-proficiency bilinguals is consistent with previous literature where groups of bilinguals who showed advantages were described as highly proficient and immersed in both languages (Hilchey & Klein, 2011; Vega & Fernandez, 2011). Findings are also consistent with a recent study by Singh and Mishra (2012), who adapted a colour-word Stroop task for eyetracking and found that

higher-proficiency Hindi-English bilinguals fixated on relevant information and resolved Stroop competition more quickly than lower-proficiency bilinguals. The proficiency measure used in the current study, a generative verbal fluency task, provides insight into the robustness of bilinguals' lexical representations and is sensitive to bilingual proficiency differences (Gollan et al., 2002). However, the letter fluency component of this task has also been linked to bilingual advantages in cognitive control when proficiency is accounted for (e.g., Luo et al., 2010), a finding that is perhaps not surprising given that correlations have been identified between cognitive control skills and a number of language tasks with high retrieval demands (e.g., Gollan et al., 2012; Linck et al., 2008; Pivneva et al., 2012) or switching components (Festman & Münte, 2012; Festman, Rodriguez-Fornells, & Münte, 2010; Prior & Gollan, 2011; Prior & MacWhinney, 2010). Therefore, since functional proficiency is likely to be measured more successfully with generative tasks that are more demanding, cognitive control abilities and measured proficiency are likely to be closely interconnected. As such, we can conclude that generative proficiency measures pattern together with a nonverbal cognitive control measure in predicting the extent and time course of parallel language activation.

Given the group-level and correlational links between parallel language activation, bilingual proficiency, and Stroop performance, the hypothesis is supported that substantial experience with parallel language activation and crosslinguistic competition resolution may be one "training ground" for bilingual advantages on Stroop-type cognitive control tasks. The idea that increased competition might result in increased use of dedicated cognitive mechanisms is grounded in the monolingual literature. Under the assumption that bilinguals use similar cognitive tools as monolinguals to support language processing, the monolingual literature provides support for within-language lexical competition (Marslen-Wilson, 1987; McClelland & Elman, 1986) and recruitment of cognitive control mechanisms to resolve competition during auditory comprehension (Desroches, Newman, & Joanisse, 2009; Gernsbacher & Faust, 1991; Swinney, 1979; Taylor, O'Hara, Mumenthaler, Rosen, & Yesavage, 2005). In bilinguals, increased competition likely comes in the form of a combination of *within-language* and *between-language* competition. Intriguingly, in addition to within-language and between-language competition, bilinguals may also face additional

lexical competition in L2 that is a result of nonnative phonetic categories (e.g. Broersma & Cutler, 2011; Weber & Cutler, 2004). For example, when within-language activation was probed in their L2 English, Dutch speakers considered an image of a *panda* more than native English speakers upon hearing *pencil*, since the first vowels of these words are confusable to native Dutch speakers (i.e., the underlined vowels are part of the same vowel category in Dutch; Weber & Cutler, 2004). In sum, given additional lexical competition in bilinguals' auditory comprehension, one source of a cognitive advantage may be increased recruitment of inhibitory control mechanisms to resolve competition. In the present study, a link between parallel language activation and cognitive control is identified in bilinguals, relative to monolinguals who do not show cross-linguistic activation and, consistently, do not recruit Stroop skills during the current eyetracking task.

The role of Stroop inhibition in bilingual language processing

In the present study, Stroop-type inhibitory control was linked to parallel language activation, but it remains an open question whether Stroop-type inhibition is indeed the specific mechanism that supports competition resolution during comprehension, or whether related types of inhibition are directly involved. Stroop-type inhibition is a reasonable candidate for involvement in competition resolution during comprehension, and can be examined within the framework of the Dimensional Overlap Model (Kornblum et al., 1999), a model that accounts for a variety of different inhibition mechanisms. On the classic Stroop task, there are 2 stimulus dimensions: the colour of a word's ink (e.g., blue, green) and the meaning of the word (e.g., blue, green). The Dimensional Overlap Model posits that this conflict between 2 dimensions of the same stimulus (i.e., stimulus–stimulus conflict) originates at the perceptual level. Similarly, in the nonlinguistic Stroop task employed in the current study, the 2 conflicting stimulus dimensions are arrow direction (right, left) and arrow location (right, left). The inhibition mechanism employed to resolve Stroop conflict may therefore be similar to the mechanism employed to resolve phonological competition because, in both cases, the perceived stimulus (e.g., a colour-word in a differently coloured ink on a classic Stroop task or an auditory word

during comprehension) initially can be mapped onto 2 concepts. That is, perceptual/conceptual conflict is inherent to one bivalent stimulus, and this conflict must be resolved in order to yield the most appropriate interpretation (e.g., the ink colour is *red* not *blue*, or the word is *cat* not *cab*).

In the current study, the Stroop effect was derived by comparing reaction time differences between congruent and incongruent trials. Previous research (Liu et al., 2004) had identified neural correlates for incongruent versus congruent Stroop conditions that were consistent with cognitive control employed during bilingual language processing (Abutalebi, 2008). Further, Blumenfeld and Marian (2011) identified a correlation between *within*-language linguistic conflict resolution and the incongruent–congruent spatial Stroop effect, also pointing to a possible link between Stroop performance and bilingual processing. In the current study, higher-proficiency bilinguals recruited cognitive mechanisms during parallel language activation that also afforded them greater skill at ignoring irrelevant information. On the Stroop task, the smaller incongruent–congruent effect was driven by shorter response times to incongruent trials, suggesting less interference from irrelevant information, as well as longer response times to congruent trials, suggesting less facilitation from irrelevant information (see Table 3). However, it remains an open question whether the facilitation and inhibition components on the Stroop task have shared or separate underlying mechanisms (e.g., MacLeod, 1991; Roelofs, 2010; van Heuven, Conklin, Coderre, Guo, & Dijkstra, 2011), and future research is needed to identify whether mechanisms that underlie facilitation and inhibition components of the Stroop task are differentially recruited during parallel language activation. In the current data, post-hoc analyses suggest that reaction times on incongruent trials were closely related to the incongruent–congruent Stroop effect, $r = .6$, $p = .001$, whereas reaction times on congruent trials were not related to the incongruent–congruent effect, $r = -.001$, $p > .5$. This pattern suggests that the Stroop inhibition component may be *primarily* responsible for the correlation with parallel language activation. Direct correlations between incongruent trial reaction times and parallel activation confirm this conclusion—for the 300–500 ms window, $r = -.2$ for incongruent trials and $.028$ for congruent trials; for the 633–767 ms window, $r = .3$ for incongruent trials and $-.006$ for congruent trials.

TABLE 3

Accuracy rates and reaction times for congruent and incongruent trials in higher-proficiency bilinguals, lower-proficiency bilinguals, and monolinguals

	Accuracy rates % (SE)			Reaction times ms (SE)		
	Congruent	Incongruent	Overall	Congruent	Incongruent	Overall
Higher-proficiency bilinguals	99.5 (.8)	89.6 (3.1)	94.5 (1.7)	380.3 (12.2)	447.2 (14.3)	413.8 (12.7)
Lower-proficiency bilinguals	99.2 (.7)	83.7 (3.0)	91.4 (1.7)	361.6 (11.8)	461.0 (13.8)	411.3 (12.3)
Monolinguals	98.6 (.5)	81.8 (2.2)	90.2 (1.2)	369.2 (8.6)	462.9 (10.1)	416.0 (9.0)

Therefore, we can conclude that the *primary* mechanism indexed by the incongruent–congruent Stroop effect and recruited to resolve parallel language activation is related to inhibition of incongruent information.

As previously discussed, the linguistic sources of bilingual advantages are likely diverse, given the wide range of language processing contexts in which bilinguals may experience higher cognitive demands. For example, a number of studies have linked bilingual processing and learning to enhanced performance on the Simon task (Bartolotti et al., 2011; Linck et al., 2008; Linck et al., 2011). Since the source of conflict on the Simon task is between stimulus and response mappings (e.g., Kornblum et al., 1999), it is possible that competition during bilingual language *production* (where activated information must be mapped onto a single output) is more likely to drive bilingual advantages on the Simon task. In addition to conflict between features within a bivalent stimulus (location, direction), the nonlinguistic Stroop task employed in the current study also includes stimulus–response conflict (Kornblum et al., 1999; Martin-Rhee & Bialystok, 2008). Specifically, the irrelevant stimulus dimension (right display side, left display side) can be either congruent or incongruent with the side where the response is made (right key, left key). Therefore, the current Stroop task requires conflict resolution at 2 levels: the stimulus level and the response level. Since the early stages of auditory word recognition do not require an explicit response component, with parallel activation effects occurring before 1000 ms post word onset, and with overt responses occurring only around 1700 ms post word onset, we reasoned that response-level conflict resolution components would not be recruited to resolve conflict during the early word recognition stages. To completely rule out the possibility that stimulus–response conflict resolution mechanisms play a role in early auditory word recognition, future work will need

to employ a nonverbal Stroop task where no stimulus–response conflict is present (e.g., Liu et al., 2004). Further research can examine how different aspects of language processing may uniquely relate and contribute to various types of cognitive control tasks.

In addition to the possibility that demands in different language contexts hone different types of cognitive control, the nature of the bilingual experience may influence the cognitive system both quantitatively and qualitatively. For example, Tao et al. (2011) found that early bilinguals showed overall reaction time advantages, whereas late bilinguals showed advantages in conflict resolution. Cognitive demands and bilingual advantages may also differ in individuals who do and do not code-switch (Green, 2011) or who engage in challenging tasks such as simultaneous interpreting (Christoffels, De Groot, & Kroll, 2006). Moreover, competition within a single processing modality (e.g., auditory) may be related to bilingual advantages. Emmorey, Luk, Pyers, and Bialystok (2008) identified better performance on the flanker task in *unimodal* but not *bimodal* bilinguals, even though cross-linguistic (i.e., crossmodal) competition has been identified during comprehension in bimodal bilinguals (Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Shook & Marian, 2012). In sum, a diverse range of factors (including language experience, type of processing, and task demands) is likely to influence the nature and extent of bilingual cognitive advantages.

CONCLUSION

In the present study, we identified direct relationships between parallel language activation and Stroop-type inhibition in early English-Spanish bilinguals. Findings suggest that bilinguals who perform well on the Stroop task show early cross-linguistic competitor activation and that higher-

proficiency bilinguals show more parallel language activation and more efficient Stroop inhibition. Results support the hypothesis that crosslinguistic competition in bilinguals engages Stroop-type domain-general inhibition, and contribute to the ongoing research effort to specify the linguistic origins of bilingual cognitive advantages.

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APPENDIX A

TABLE A1

Stimulus list for the crosslinguistic eyetracking task: English targets and Spanish competitors, with filler words

	<i>English target</i>	<i>Spanish competitor</i>	<i>Competitor translation into English</i>	<i>Filler 1</i>	<i>Filler 2</i>
1	comb	conejo	rabbit	sword	rail
2	pea	pie	foot	window	boy
3	peal	pila	battery	whistle	globe
4	pool	pulgar	thumb	candle	log
5	plug	plancha	iron	button	mail
6	mice	maíz	corn	jar	glove
7	pliers	playa	beach	wood	collar
8	luggage	lata	can	pigeon	skis
9	eagle	iglesia	church	letter	present
10	poodle	puño	fist	ruler	olive
11	cup	caballo	horse	wheel	bench
12	song	sombrero	hat	queen	bear
13	puppy	pan	bread	music	rose
14	corn	cola	tail	skirt	bride
15	yarn	llave	key	sink	roof
16	soap	sobre	envelope	castle	lion
17	nun	naranja	orange	pipe	belt