Journal of Cognitive Psychology

ISSN: 2044-5911 (Print) 2044-592X (Online) Journal homepage: http://www.tandfonline.com/loi/pecp21

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JOURNAL OF COGNITIVE PSYCHOLOGY, 2017
https://doi.org/10.1080/20445911.2017.1321553

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Cross-linguistic phonotactic competition and cognitive control in bilinguals

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ABSTRACT
The current study examines the relation between cognitive control and linguistic competition resolution at the sublexical level in bilinguals. Twenty-one Spanish–English bilinguals and 23 English monolinguals completed a non-linguistic Stroop task (indexing inhibitory control) and a linguistic priming/lexical decision task (indexing Spanish phonotactic-constraint competition during English comprehension). More efficient Stroop performance (i.e. a smaller Stroop effect) in bilinguals was associated with decreased competition from Spanish phonotactic constraints during English comprehension. This relation was observed when nonword targets overlapped in phonotactic constraints and phonological form with preceding *cognate* primes (e.g. prime: *stable* (*Spanish*: *estable*)/target: *esteriors*). Findings suggest a link between non-linguistic cognitive control and co-activation of linguistic structures at the sublexical level in bilinguals.

ARTICLE HISTORY
Received 18 July 2016
Accepted 18 April 2017

KEYWORDS
Bilingualism; parallel activation; cognitive control; competition resolution; phonotactic constraints

During language processing, bilinguals may experience simultaneous activation of both languages, or parallel activation. Parallel activation of the two languages may increase overall cognitive load as competition from an irrelevant language is overcome (e.g. Blumenfeld & Marian, 2013; Freeman, Shook, & Marian, 2016; Kroll & Bialystok, 2013; Kroll, Bobb, Misra, & Guo, 2008; Linck, Hoshino, & Kroll, 2008). For example, bilinguals access both within- *and* between-language competitor words during auditory comprehension and have to inhibit irrelevant words across languages (e.g. *plug* activates *plum* and *plancha*/iron for a Spanish–English bilingual; Blumenfeld & Marian, 2013). In contrast, when monolinguals hear *plug*, they may activate multiple competing words *within* the same language only (e.g. phonological competitor *plum*, e.g. Blumenfeld & Marian, 2011; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Therefore, bilinguals may rely on cognitive control during language processing to inhibit not only within-, but also between-language interference in order to select the target word (e.g. Blumenfeld & Marian, 2011, 2013; Giezen, Blumenfeld, Shook, Marian, & Emmorey, 2015; Mercier, Pivneva, & Titone, 2014).

The involvement of inhibitory control skills during bilingual language processing has been documented across various tasks indexing phonological (Blumenfeld & Marian, 2011, 2013; Blumenfeld, Schroeder, Bobb, Freeman, & Marian, 2016; Mercier et al., 2014), lexical (Linck et al., 2008; Linck, Schwieter, & Sunderman, 2012; Prior & Gollan, 2011), semantic (Martín, Macizo, & Bajo, 2010), and syntactic co-activation (Linck et al., 2008; Teubner-Rhodes et al., 2016; see Freeman, Shook, et al., 2016, for review). In the current study, we seek to examine the relation between cognitive control and cross-linguistic competition resolution (i.e. how individuals manage and suppress interfering cues while focusing on relevant information) at the *sublexical* level. Specifically, we consider how cognitive control abilities relate to co-activation of *phonotactic constraints* (i.e. rules for combining speech sounds) during comprehension.

The relation between non-linguistic and linguistic cognitive control has been observed during language comprehension (e.g. Blumenfeld & Marian, 2011, 2013; Mercier et al., 2014). Blumenfeld and Marian (2011) found that bilinguals', but not monolinguals', performance on a non-linguistic

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Stroop arrows task was associated with lexical competition resolution during auditory word recognition. The non-linguistic Stroop task indexed conflict between two overlapping perceptual dimensions within the same stimulus: arrow direction and location (Blumenfeld & Marian, 2014; Kornblum, Stevens, Whipple, & Requin, 1999). Relatedly, the linguistic eye-tracking measure probed phonological-cohort competition within the same language (e.g. target: *plum*, competitor: *plug*). Results from Blumenfeld and Marian (2011) indicated that better Stroop inhibition was associated with more efficient competitor-word inhibition in bilinguals. Mercier et al. (2014) similarly found that more refined inhibitory control on a battery of non-linguistic cognitive control tasks (i.e. Stroop, Simon, antisaccade) was related to decreased *within*- and *between*-language competition on a word identification task in bilinguals. Moreover, Blumenfeld and Marian (2013) examined the time course of between-language competition using phonological cohorts. Results demonstrated that more efficient competition resolution on the Stroop task was associated with early competitor activation (300–500 ms post-word onset) followed by later competitor inhibition (633–767 ms post-word onset).

Bilinguals may thus employ domain-general cognitive control mechanisms to manage linguistic competition. More efficient cognitive abilities appear to be associated with decreased co-activation of the irrelevant language. If the link between non-linguistic processing and managing sublexical competition is similar to the links demonstrated for phonology, semantics, and syntax, then performance may be related across a non-linguistic task measuring cognitive control and a linguistic task involving phonotactic-constraint competition. However, different components of language may be associated with cognitive control in disparate ways. Therefore, competition at the sublexical level may involve non-linguistic cognitive control in a different way than identified in previous studies.

Research on sublexical processing suggests that bilinguals may co-activate phonotactic constraints and phonetic characteristics from their other language during comprehension (Amengual, 2016; Broersma & Cutler, 2011; Carlson, Goldrick, Blasingame, & Fink, 2016; Durlik, Szewczyk, Muszyński, & Wodniecka, 2016; Freeman, Blumenfeld, & Marian, 2016; Weber & Cutler, 2006) and production (Amengual, 2016; Goldrick, Runnqvist, & Costa, 2014; Yavas & Someillan, 2005). An example of language-specific phonotactic constraints is that of word-initial s+ consonant clusters (e.g. English: *stable*) in Spanish–English bilinguals. S+ consonant clusters are legal at word onsets in English but are illegal in Spanish; in Spanish, an epenthetic "e" (i.e. the addition of a vowel) must be added to render the word acceptable (e.g. Spanish: *estable*). Thus, the epenthetic "e" with the s+ consonant cluster satisfies a phonotactic constraint in Spanish. If a Spanish–English bilingual is listening to auditory input or producing words in English, s/he may access Spanish competitors that conform to the phonotactic constraint (e.g. *strong*, Spanish *estricto*, or *strict*, Carlson et al., 2016; Freeman, Blumenfeld, et al., 2016). However, the cognitive control mechanism(s) that bilinguals use to regulate phonotactic-constraint activation has yet to be determined.

The cognitive control mechanisms modulating interference from sublexical structures may depend on the extent to which both languages are activated. We found that greater activation of Spanish phonotactic constraints occurred when bilinguals were primed with English *non*-cognates (e.g. English: *strong/*Spanish: *fuerte*) than with cognates (e.g. English: *stable/*Spanish: *estable*) (Freeman, Blumenfeld, et al., 2016). In previous studies, cognates have been shown to facilitate access of both languages in bilinguals (Amengual, 2016; Blumenfeld, Bobb, & Marian, 2016; Blumenfeld & Marian, 2007; Christoffels, Firk, & Schiller, 2007; Costa, Caramazza, & Sebastian-Galles, 2000; Dijkstra & Van Heuven, 2002; Goldrick et al., 2014; Hoshino & Kroll, 2008). The results from Freeman, Blumenfeld, et al. (2016), and Hoshino and Kroll (2008) suggest that during cognate processing, more cognitive resources may be deployed to suppress highly similar representations from the non-target language. For example, bilinguals may suppress phonotactic-constraint access from Spanish so that the relevant language can be selected (English).

The current study

In the current study, we related performance on a non-linguistic Stroop arrows task (Blumenfeld & Marian, 2014; Giezen et al., 2015) to performance on an English phonological-priming lexical decision (PPLD) task (Freeman, Blumenfeld, et al., 2016). To examine competition resolution abilities independent of language skill, participants were presented with an arrow on the left or right side of a visual display. A left/right keyboard button press response

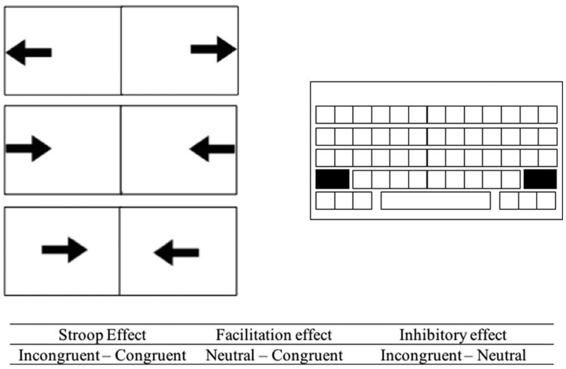

Figure 1. Non-linguistic Stroop task procedure and calculation of competition effects. The top window represents congruent trials, the middle window represents incongruent trials, and the bottom window represents neutral trials. Participants responded to right- or left-pointing arrows by pressing the right or left "Shift" key, respectively.

was used to indicate the direction of the arrow. Congruent (arrow location and direction matched), incongruent (arrow location and direction mismatched), and neutral trials (arrow appeared in the centre of the screen, pointing right or left) were included. We calculated measures of non-linguistic Stroop competition across conditions (see Figure 1 for conditions and competition effects on the Stroop task).

We expected a relation between performance on the non-linguistic Stroop task and performance on the linguistic PPLD task.

Linguistic competition on the PPLD task

The PPLD task examined competition from Spanish phonotactic constraints during English comprehension (See Figure 2 for PPLD task procedure). To trigger covert activation of Spanish phonotactic constraints, the PPLD task included English auditory primes that conflicted with the Spanish "e" epenthesis constraint (cognate: *stable*, non-cognate: *strong*) as well as control primes (*workers*). The auditory primes were followed by visual lexical-decision targets to probe for activation of Spanish phonotactic constraints.

The critical targets were English-like nonwords across three conditions (see Table 1 for sample stimuli):

(a) A phonotactic-constraint-and-form overlap condition, where the English nonwords overlapped with preceding primes in phonology and conformed to the Spanish phonotactic "e" constraint (e.g. nonword: *esteriors*). This condition probed the extent to which Spanish phonotactic constraints and phonology had been activated by the English prime, by examining both Spanish phonotactic constraint ("e" onset) and Spanish phonological overlap competition at the onset ("es" + consonant overlap).
(b) A phonotactic-constraint-only condition that included the "e" onset (e.g. nonword: *elopevent*). This condition allowed us to dissociate covert activation of the Spanish epenthetic "e" from broader phonological activation by separating phonotactic-constraint overlap from phonological-form overlap ("e" onset overlap only).
(c) A control condition had no overlap in phonology or constraint (e.g. nonword control: *hereander*). The nonword controls served as a baseline condition measuring response times to nonwords that did not overlap with Spanish in phonotactic constraints or phonological form.

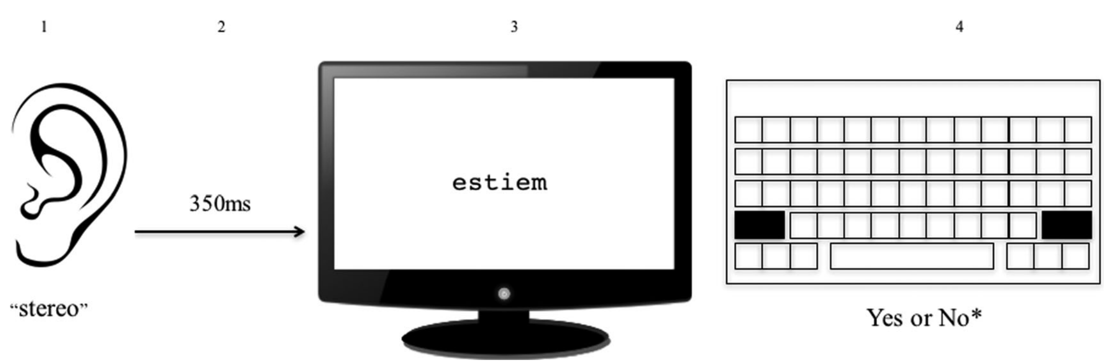

Figure 2. PPLD task procedure. In the PPLD task, participants first hear an auditory prime (e.g. *stereo*). After the offset of the prime, participants view a word or a nonword (e.g. *estiem*) on the computer screen and perform a lexical decision task (*Yes response = English real word, No response = nonword). Figure adapted from Freeman, Blumenfeld, et al. (2016).

Table 1. Sample stimuli across conditions on the PPLD task.

Auditory prime	Phonotactic-constraint-and-form nonword target	Phonotactic-constraint-only English-like nonword target	English-like nonword control	Control word
stereo (*cognate*)	estiem	edtent	blanth	clingy
spicy (*non-cognate*)	espanded	ebvision	bountary	namedrop
travel (*control*)	estrance	edection	langsune	untangle

We also included control words and fillers (e.g. *flattened*) to balance the word-to-nonword ratio.

The PPLD task has previously revealed that Spanish–English bilinguals accessed Spanish phonotactic constraints during English comprehension, with greater cross-linguistic activation following non-cognate than cognate primes (Freeman, Blumenfeld, et al., 2016). Specifically, bilinguals were faster to respond to phonotactic-constraint-and-form *and* phonotactic-constraint-only trials (indexing cross-linguistic activation) when primed with non-cognates, relative to control trials, and also faster to respond to phonotactic-constraint-and-form trials when primed with cognates, relative to control trials. The novel contribution of the present study is that we examine engagement of cognitive control during cross-linguistic processing of phonotactic constraints by comparing performance on a non-linguistic Stroop task with performance on the PPLD task. To do so, we calculated measures of linguistic competition across conditions. (See Table 2 for competition effects on the PPLD task.)

Relation between linguistic and non-linguistic cognitive control

We mapped bilinguals' non-linguistic Stroop competition skills to phonotactic-constraint competition across languages. The incongruent stimuli on the Stroop task elicited perceptual conflict with arrow location (left, right) and direction (pointing left or right) mismatching on the screen. The experimental stimuli in the English PPLD task created cross-linguistic conflict with phonotactic-constraint competition from the irrelevant language (Spanish). Previous research has identified a link between non-linguistic cognitive control and phonological co-activation (e.g. Blumenfeld & Marian, 2013; Mercier et al., 2014). We thus predicted that better performance on the Stroop task would relate to less phonotactic-constraint competition from the non-target language within bilinguals. Such findings would suggest that more efficient non-linguistic cognitive control abilities are associated with better management of cross-linguistic competition at the sublexical level.

Table 2. Calculations of competition effects on the PPLD task .

Phonotactic-constraint-and-form competition (PCF) effect	Phonotactic-constraint-only competition (PC) effect
Cognate prime and nonword control target	Cognate prime and nonword control target
–	–
Cognate prime and PCF target	Cognate prime and PC target
Non-cognate prime and nonword control target	Non-cognate prime and nonword control target
–	–
Non-cognate prime and PCF target	Non-cognate prime and PC target

Notes: Reaction times to phonotactic-constraint-and-form and phonotactic-constraint-only nonword targets (preceded by either cognate or non-cognate primes) were subtracted from reaction times to nonword control targets (preceded by either cognate or non-cognate primes).

Furthermore, we predicted that if an association were to emerge between non-linguistic competition resolution abilities and phonotactic-constraint competition in bilinguals, the correlation would be strongest in the presence of cognate primes. Cognates have been shown to facilitate lexical access across languages (e.g. Blumenfeld & Marian, 2007; Christoffels et al., 2007; Costa et al., 2000; Dijkstra & Van Heuven, 2002; Hoshino & Kroll, 2008). The presence of cognates may therefore require greater cognitive resources to suppress activation of the irrelevant language at the sublexical level. Consistently, Linck et al. (2008) found that better performance on the Simon task was linked to decreased facilitation from cognates during picture naming. In the current study, phonotactic constraints for cognates differed across languages (e.g. *stable/estable*). Thus, there might be a need to recruit more cognitive resources to suppress interference from the irrelevant language in the presence of cognates than in the presence of non-cognates (e.g. *strong/fuerte*).

Method

Participants

Twenty-one Spanish–English bilinguals and 23 English monolinguals were included (from

Table 3. Linguistic and cognitive background of Spanish–English bilingual ($n = 21$) and English monolingual ($n = 23$) participants.

	Bilinguals Mean (SE)	Monolinguals Mean (SE)
Age	23.67 (0.76)	22.95 (0.74)
Age of Spanish acquisition	0.48 (0.13)	–
Age of English acquisition**	6.33 (0.43)	0.18 (0.08)
Age proficient in English**	9.95 (0.98)	3.36 (0.39)
Time since English acquisition**	17.33 (0.73)	22.78 (0.75)
Time fluent in English**	13.71 (0.97)	19.40 (0.85)
Current exposure to Spanish	37.57% (4.21)	–
Current exposure to English**	61.67% (4.48)	98.65% (0.69)
Foreign accent in Spanish (0–10 scale)	2.00 (0.49)	–
Foreign accent in English (0–10 scale)*	2.86 (0.59)	0.73 (0.56)
Spanish receptive vocabulary (NIH Toolbox)	116.85 (2.98)	–
English receptive vocabulary (NIH Toolbox)	111.13 (3.47)	118.86 (3.39)
Self-reported Spanish proficiency (0–10 scale)	8.98 (0.14)	–
Self-reported English proficiency (0–10 scale)	8.95 (1.13)	9.83 (0.05)
WASI, matrix reasoning	29.29 (0.55)	28.78 (0.61)
Backward digit span	7.19 (0.94)	10.14 (1.10)

*$p < .01$.
**$p < .001$.

Freeman, Blumenfeld, et al., 2016).[1] Participants completed the Language Experience and Proficiency Questionnaire (LEAP-Q) (Marian, Blumenfeld, & Kaushanskaya, 2007) to assess language background information and current language exposure, and to ensure that participants met the criteria for the study. Participants also performed the Wechsler Abbreviated Scale of Intelligence (WASI; PsychCorp, 1999) to index non-verbal cognitive reasoning; backward digit span (numbers reversed, Woodcock, McGrew, & Mather, 2001/2007) to assess working memory; and the National Institutes of Health Cognition Toolbox Battery (NIH Toolbox CB, 2013), specifically the picture vocabulary test, to account for English (bilinguals and monolinguals) and Spanish (bilinguals only) proficiency. See Table 3 for participants' linguistic and cognitive profiles.

Materials and design

Non-linguistic Stroop arrows task

The non-linguistic Stroop task (e.g. Blumenfeld & Marian, 2014; Giezen et al., 2015) indexed cognitive control abilities, specifically, the Stroop, facilitation, and inhibition effects. The Stroop task was programmed in MatLab (Psychtoolbox add-on) (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). On each trial, participants were presented with a black arrow (left, right, or centre) on a visual display and responded using the left/right "Shift" keys indicating the direction of the arrow. Arrow location and direction corresponded (congruent trials), did not correspond (incongruent trials), or the arrow appeared in the centre of the visual display (neutral trials) (see Figure 2). The neutral condition provided a baseline against which Stroop facilitation and inhibition could be indexed (Blumenfeld & Marian, 2014). The task consisted of 200 trials (60 left-congruent, 60 right-congruent, 20 left-incongruent, 20 right-incongruent, 20 neutral-left, and 20 neutral-right), and an additional 20 practice trials (4 neutral, 4 incongruent, 12 congruent). The ratio of incongruent to congruent trials was 1:3.

Thus, the within-subjects independent variable was trial type (congruent, incongruent, neutral) and the between-subjects independent variable was language group (bilingual, monolingual), yielding a 3×2 mixed factorial design. The dependent variables included accuracy and reaction time identifying the direction of the arrow. Reaction times were measured from the onset of the stimulus picture (arrow). We calculated competition effects based on reaction-time differences between congruent, incongruent, and neutral trials:

- The Stroop effect: reaction times to incongruent (arrow location and direction mismatch) minus congruent trials (arrow location and direction match).
- The Stroop facilitation effect: reaction times to neutral trials (arrow appears in the centre of the screen) minus congruent trials.
- The Stroop inhibition effect: reaction times to incongruent minus neutral trials.

Cross-modal PPLD task

The English PPLD task indexed phonotactic-constraint competition from Spanish (the epenthetic "e" onset). English cognate and non-cognate primes were used that started with either "sp" or "st" and thus violated the Spanish phonotactic constraint. Following auditory primes, visual targets included English-like nonwords that conformed to the Spanish rule, overlapping in phonotactic constraint and phonological form ("es" + consonant onset), nonwords that conformed to the phonotactic constraint only ("e" onset), and nonwords with unrelated onsets. The word-to-nonword ratio was set to

[1]In Freeman, Blumenfeld, et al. (2016), we tested 22 Spanish-English bilinguals and 23 English monolinguals. We included 21 bilinguals in the current study because of equipment malfunction during the Stroop task for one of the bilingual participants.

1:1 by including control word and filler trials. The PPLD task was programmed in MatLab (Psychtoolbox add-on) (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). See Freeman, Blumenfeld, et al. (2016) for additional information regarding stimulus characteristics. To correlate performance with the non-linguistic Stroop task, we calculated linguistic competition effects based on reaction time and accuracy differences across prime and target conditions (also see Table 2):

- To examine competition effects of cognate primes followed by phonotactic-constraint-and-form (CPCF) targets, we subtracted reaction times and accuracy rates to these CPCF trials (e.g. *stable*/*esteriors*) from cognate primes followed by nonword control trials (e.g. *stable*/*hereander*).
- To measure competition effects of cognate primes followed by phonotactic-constraint-only (CPC) targets, we subtracted reaction times and accuracy rates to these CPC trials (e.g. *stable*/*elopevent*) from cognate primes followed by nonword control trials (e.g. *stable*/*hereander*).
- We repeated the same process for non-cognate primes (e.g. *strong*) followed by PCF and PC targets (NPCF, NPC).

The within-subjects independent variable was competition effect type (CPCF, CPC, NPCF, NPC) and the between-subjects independent variable was language group (bilingual, monolingual), resulting in a 4×2 mixed factorial design. The dependent variables were accuracy and reaction-time difference scores.

Procedure

Before performing the experimental tasks, participants completed the LEAP-Q (Marian et al., 2007). The experimental tasks included the non-linguistic Stroop arrows task (Blumenfeld & Marian, 2014; Giezen et al., 2015) to measure competition resolution abilities independent of language, and the cross-modal PPLD task (auditory prime, visual target) (Freeman, Blumenfeld, et al., 2016) to examine cross-linguistic phonotactic competition.

Participants were seated in a quiet room with an iMac computer. On the non-linguistic Stroop task, participants were instructed to respond to the direction of the arrow (left, right) and to ignore the location of the arrow on the screen (left, right, centre) as quickly and accurately as possible. Trials were presented in a fixed pseudo-randomized order. Each trial began with a fixation crosshair presented for 500 ms in the centre of the screen. The stimulus display then followed for 700 ms, and the trial ended with a blank screen for 800 ms.

On the English PPLD task, participants were instructed to pay attention to the word they heard (auditory prime: cognate, non-cognate, control) while viewing a central fixation crosshair on the computer screen. Next, 350 ms after the offset of the auditory prime, participants viewed a visual target (PCF nonword, PC nonword, nonword control, control word). A lexical decision was made on the visual target. Left/right shift keys on the keyboard corresponded to yes (word)/no (nonword) responses. Participants were instructed to respond as quickly and accurately as possible. Visual targets were displayed in the centre of a white screen in black, size 16 font, Courier. The targets were visible until the participant made a response or for 3,000 ms after the onset of the display. Participants completed 12 practice trials and then moved on to the experiment proper. Participants performed the remaining cognitive and language-proficiency measures, then were debriefed about the study and compensated. The total study duration was approximately two hours.

Coding and analyses

Within the Stroop task, we indexed three competition effects (Stroop, facilitation, and inhibition effects) based on reaction-time differences to congruent, incongruent, and neutral trials. Within the PPLD task, we measured four effects of phonotactic-constraint competition (CPCF, CPC, NPCF, and NPC competition effects, see Table 2) from accuracy and reaction-time difference scores. The scores were calculated in order to correlate competition effects across the non-linguistic Stroop and PPLD tasks. Outlier analyses were also conducted to ensure that all participants' competition effects were within 2.5 standard deviations of the mean. Lastly, to examine how cognate status mediated the relation between bilinguals' Stroop (Stroop, facilitation, and inhibition) and PPLD performance (CPCF, CPC, NPCF, NPC), we used a *post hoc* mixed-linear model (MLM: Jaeger, 2008) with the lmer Test package in *R*. Target type was the intercept term (PCF or PC competition effect); prime type (cognate, non-cognate) and *z*-score transformed Stroop competition effects were the fixed effects;

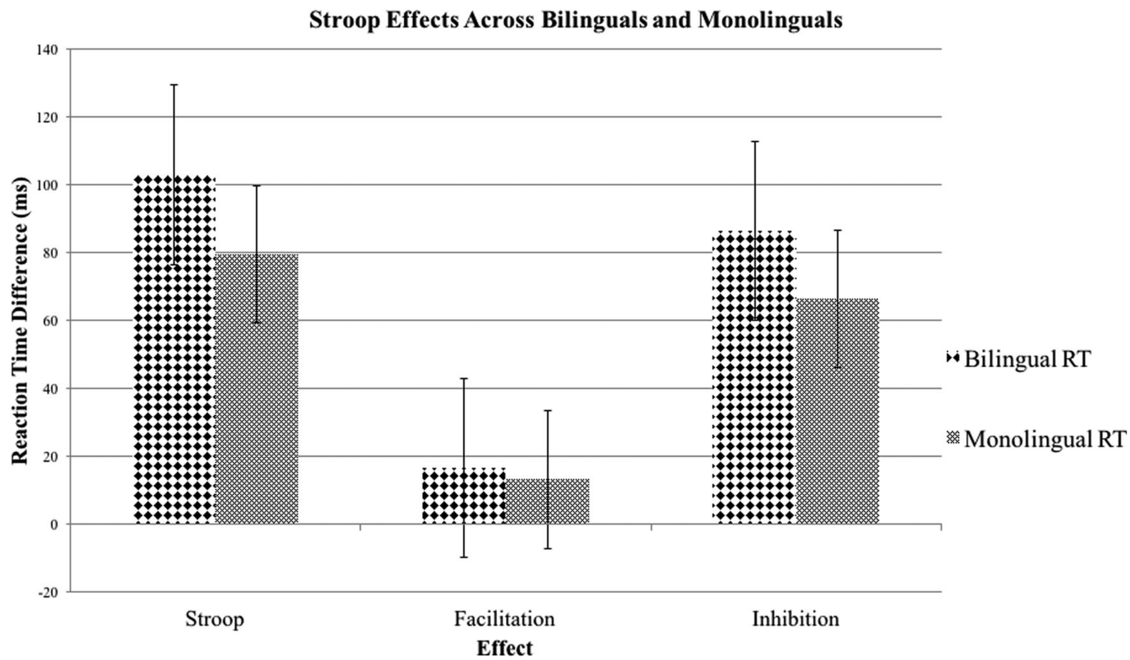

Figure 3. Bilingual vs. monolingual performance (reaction-time difference scores) on the non-linguistic Stroop arrows task across Stroop, facilitation, and inhibition effects. Error bars = 2 standard errors.

and items and participants served as random effects on the slope.

Results

Results are reported as follows: (1) competition effects on the Stroop task, (2) competition effects on the PPLD task, (3) performance correlations across the Stroop and PPLD tasks, and (4) a *post hoc* confirmatory MLM analysis across the Stroop and PPLD tasks.

Competition effects on the Stroop task

We examined non-linguistic cognitive control abilities on the Stroop task. We conducted a 3 (competition effect: Stroop, facilitation, inhibition) × 2 (language group: bilingual, monolingual) ANOVA to probe effects of non-linguistic competition across participants. For competition effects, a main effect was observed, F (2, 84) = 60.87, $p < .001$, $\eta_p^2 = 0.59$. Follow-up Bonferroni-corrected t-tests revealed that participants showed a greater Stroop effect ($M = 91$ ms, $SE = 10$) than facilitation effect ($M = 15$ ms, $SE = 5$), t (43) = 8.02, $p < .001$, $d = 1.51$. Participants also had a greater Stroop effect than inhibition effect ($M = 76$ ms, $SE = 8$), t (43) = 2.95, $p = .01$, $d = 0.26$. In addition, participants demonstrated a greater inhibition effect than facilitation effect, t (43) = −9.48, $p < .001$, $d = 1.42$. There were no other significant main effects or interactions.

Planned follow-up Bonferroni-corrected t-tests revealed no significant differences across bilinguals and monolinguals on the Stroop effect (incongruent minus congruent trials), on the facilitation effect (neutral minus congruent trials), or on the inhibition effect (incongruent minus neutral trials) ($ps > .05$). Thus, bilinguals and monolinguals demonstrated equivalent Stroop performance.[2] See Figure 3 for bilingual/monolingual difference scores on the three Stroop measures.

Competition effects on the PPLD task[3]

Competition effects on the PPLD task were calculated to correlate performance across the linguistic and

[2]Previous studies that have identified bilingual advantages on the Stroop task employed considerably larger sample sizes (Bialystok, Craik, & Luk, 2008) and bilingual advantages on cognitive control tasks, relative to monolingual peers, are generally small or absent for young adults (e.g. Bialystok, Martin, & Viswanathan, 2005). In the current study, the goal was not to identify bilingual advantages but to examine relations between non-linguistic and linguistic competition.

[3]See Freeman, Blumenfeld, et al. (2016) for detail on repeated-measures ANOVAs on the PPLD task. In brief, two 3 (prime: cognate, non-cognate, control) × 4 (target: phonotactic-constraint-and-form overlap nonword, phonotactic-constraint-only nonword, nonword control, word control) × 2 (group: monolingual, bilingual) ANOVAs were performed on (1) reaction times and (2) accuracy rates. For RT, there was a main effect of

Table 4. Means and standard deviations of competition effects (reaction-time differences in milliseconds) on the PPLD task. Mean (SD).

Competition effect	Monolinguals	Bilinguals
Cognate prime, phonotactic-constraint-and-form target (CPCF)	10 (47)	65 (80)
Cognate prime, phonotactic-constraint-only target (CPC)	−1 (42)	40 (101)
Non-cognate prime, phonotactic-constraint-and-form target (NPCF)	25 (48)	70 (70)
Non-cognate prime, phonotactic-constraint-only target (NPC)	15 (51)	63 (85)

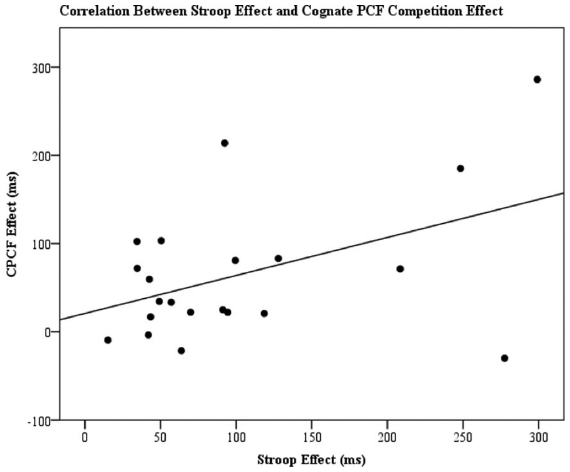

Figure 4. Correlation between cognate, phonotactic-constraint-and-form (CPCF) competition effect and Stroop effect.

non-linguistic measures. Two 4 (competition effect: cognate, phonotactic constraint-and-form (CPCF); cognate, phonotactic constraint-only (CPC); non-cognate, phonotactic constraint-and-form (NPCF); non-cognate, phonotactic constraint-only (NPC)) × 2 (language group: bilingual, monolingual) ANOVAs were conducted for accuracy and reaction-time differences of competition effects across participants. There were no significant main effects or interactions for accuracy ($ps > .20$). For reaction times, a main effect of language group emerged, $F(1, 42) = 9.12, p < .01, \eta_p^2 = 0.18$. The main effect indicated that bilinguals ($M = 59$ ms, $SE = 11$) showed greater reaction-time difference scores on these cross-linguistic competition effects than monolinguals ($M = 12$ ms, $SE = 11$). This finding confirms that bilinguals experienced competition from Spanish phonotactic constraints during English comprehension (See Table 4 for means and standard deviations of competition effect reaction-time differences).

Performance correlations across the Stroop and PPLD tasks

To examine the relation between Stroop competition effects (Stroop, facilitation, inhibition) and PPLD competition effects (CPCF, CPC, NPCF, NPC), correlations were calculated across tasks. Based on previous studies examining such links at other linguistic levels (e.g. Blumenfeld & Marian, 2011, 2013; Mercier et al., 2014; Teubner-Rhodes et al., 2016), we predicted that more efficient performance on the Stroop task would be related to decreased competition from the "e" phonotactic constraint for bilinguals. In the bilingual group, a significant positive correlation was observed between the Stroop effect and the CPCF effect ($r = 0.45$, $p = .039$). As expected, this correlation suggested that a smaller Stroop effect (better performance) was associated with a decreased CPCF competition effect, or less Spanish phonotactic-constraint competition in bilinguals primed with cognates (see Figure 4). The corresponding correlation effect was not significant for monolinguals ($r = -0.16$, $p = .48$).

One other positive correlation was observed between the Stroop facilitation effect and the CPC competition effect ($r = 0.57$, $p = .01$) in bilinguals. However, an outlier analysis revealed that two outliers (one participant's CPC competition effect, one participant's Stroop facilitation effect) skewed this correlation towards significance. Once the outliers were removed, the correlation was no longer significant ($r = -0.01$, $p = .96$). No other correlations were observed for cognates and non-cognates with monolinguals ($rs = -0.28$–0.28, $ps > .05$) or bilinguals ($rs = -0.33$–0.16, $ps > .05$). Thus, Stroop-type competition resolution appears to modulate the extent to which phonotactic constraints are accessed from the non-target language (Spanish), within one context of cross-linguistic phonotactic-constraint activation (i.e. CPCF condition).

group, $F(1, 43) = 11.70$, $p < .01$; monolinguals ($M = 656$ ms responded faster to lexical decision targets than bilinguals ($M = 881$ ms), $p < .01$. A main effect of visual target condition was also found, $F(3, 129) = 16.02$, $p < .001$. Bilinguals were faster on phonotactic-constraint-and-form nonwords and phonotactic-constraint-only nonwords when primed with non-cognates, as well as faster to respond to phonotactic-constraint-and-form nonwords when primed with cognate than control trials. For accuracy, there was a main effect of target, $F(3, 129) = 4.26$, $p < .01$, with participants more accurate on phonotactic-constraint-and-form nonword trials ($M = 96.89\%$) than on word control trials ($M = 94.87\%$), $p = .045$. In sum, bilinguals experienced co-activation of phonotactic constraints from Spanish during English language comprehension.

Table 5. Summary of fixed effects in the MLM for the Stroop effect and phonotactic-constraint-and-form (PCF) competition effect for bilinguals (by-subjects and by-items).

	β	Standard error	*t*	*p*
PCF competition effect: Intercept	27.40	22.76	1.20	.23
Prime: cognate vs. non-cognate	−52.36	45.52	−1.15	.25
Stroop effect (*z*-score)	−3.00	15.95	−.19	.85
Prime * Stroop effect	61.39	31.90	1.92	.05

Post hoc *confirmatory MLM analysis across the Stroop and PPLD tasks*

Last, a MLM was employed with bilinguals to validate the differential effects observed for cognate and non-cognate primes. Specifically, we examined how cognate status (cognates, non-cognates) affected the relation between performance on the non-linguistic Stroop task and the PPLD task. The predicted value (dependent variable) was the difference in reaction time between the phonotactic-constraint-and-form and nonword control conditions. The model included fixed effects of prime (cognate, non-cognate), and the *z*-transformed (centred) Stroop effect as continuous (independent) variables across participants, subjects and items as random effects, and an interaction between the prime and Stroop effect on the PCF competition effect (see Table 5).

As expected from correlational findings, the model revealed a marginally significant interaction between Stroop and cognate effects, suggesting that the influence of the Stroop effect on the PCF competition effect was stronger with cognates than non-cognates, $\beta = 61.39$, $SE = 31.90$, $t = 1.92$, $p = .05$. This analysis confirmed that the observed correlation between Stroop performance and phonotactic-constraint competition held only with and was stronger for cognates than for non-cognates.

Discussion

In the current study, we examined the relation between non-linguistic and linguistic sublexical competition within bilinguals and monolinguals. Specifically, we investigated the link between non-linguistic Stroop competition resolution and phonotactic-constraint interference from the irrelevant language. Findings demonstrated that smaller Stroop effects (better performance) were associated with decreased competition from Spanish phonotactic constraints when cognates were present during language comprehension in bilinguals. In other words, better non-linguistic cognitive control abilities may relate to greater efficiency with managing sublexical competition from the non-target language in the presence of cognates.

Linguistic and non-linguistic competition resolution

Results align with findings from previous studies in which bilinguals who demonstrated more efficient cognitive control abilities also experienced decreased competition from the irrelevant language (Blumenfeld & Marian, 2013; Linck et al., 2012; Mercier et al., 2014; Teubner-Rhodes et al., 2016). In the current study, better cognitive control skills were associated with less competition from phonotactic constraints when cognates were present. Linck et al. (2008) similarly demonstrated that efficient inhibitory control abilities on the Simon task were associated with decreased cognate activation and facilitation on a picture naming task. Thus, during production, inhibition may help bilinguals hone in on language-specific phonetic realizations of cognates (Nip & Blumenfeld, 2015). Increased cognitive control may dampen access of irrelevant-language phonotactic constraints in order to select the relevant language. To our knowledge, we demonstrate here for the first time that cognitive control may also be employed to suppress access to the irrelevant language's sublexical representations during comprehension.

This domain-general relation between competition resolution abilities may have occurred due to two incongruent aspects within stimuli on both the Stroop and PPLD tasks. On the non-linguistic Stroop task, participants experienced perceptual conflict with arrow location and arrow direction. For example, an arrow pointing to the right, however appearing on the left side of the screen, may have invoked a right- or left-button click on the keyboard. Participants had to ignore arrow location and respond to arrow direction. The incongruent linguistic aspects on the PPLD task stemmed from the English auditory prime that violated the Spanish "e" phonotactic constraint (e.g. *stable*). Bilinguals accessed phonological- and phonotacticcohort words with the “e” onset from the irrelevant language (e.g. Spanish: *estudio*/“study”).

Thus, the Stroop effect measured participants’ ability to resolve interference between competing perceptual aspects of a stimulus (arrow location on the screen and arrow direction) and, relatedly, the cognate, phonotactic-constraint-and-form (CPCF) effect indexed competition from the irrelevant language due to the mismatch of phonotactic constraints across languages. Analogous to previous studies (e.g. Blumenfeld & Marian, 2011, 2013; Giezen et al., 2015; Mercier et al., 2014), we found further evidence for the domain-general relation across tasks in which participants experienced similar conflict (i.e. where they had to ignore the irrelevant aspect of the stimulus). In summary, performance across the two measures indicates that individual differences in bilinguals’ use of phonotactic constraints may have been driven in part by individual differences in cognitive control skills.

Implications

Current models of bilingual language processing have explained how cross-linguistic phonotactic constraints are accessed during language *production* (e.g. Word-form Encoding by Activation and VERification++ Model, Roelofs, & Verhoef, 2006). Theoretical accounts have also been formulated to describe the cognitive control mechanisms bilinguals may use to manage competition from the irrelevant language (e.g. Inhibitory Control Model, Green, 1998). However, language *comprehension* models have yet to integrate the link between cognitive control abilities and phonotactic-constraint competition in bilinguals within the same framework. The Bilingual Interactive Activation+ (BIA+) (Dijkstra & Van Heuven, 2002) and Bilingual Language Interaction Network for Comprehension of Speech (BLINCS) (Shook & Marian, 2013) models of bilingual language comprehension suggest that bilinguals access both languages in parallel and that inhibition is involved at the *lexical* level in suppressing activation from the non-target language. Our study suggests that competition resolution may be engaged to regulate *sublexical* phonotactic-constraint access from the irrelevant language during comprehension. We can thus extend bilingual language processing models such as the BIA+ and BLINCS to account for the similar cognitive control mechanisms that are potentially recruited when bilinguals co-activate sublexical phonotactic constraints.

Limitations and future directions

The bilinguals in the current study had experience with English and Spanish over a long period of time, as indicated by their early age of L2 acquisition (around age 6). Thus, these long-term bilinguals likely had considerable practice with suppressing conflict from their irrelevant language (competition resolution). Different findings might be expected with bilinguals who had less experience in the L2 or a later age of L2 acquisition. Previous studies have demonstrated that cognitive control abilities change with L2 experience (e.g. Luk, de Sa, & Bialystok, 2011). We suspect that bilinguals with less L2 experience would demonstrate less refined cognitive control skills (i.e. less efficient Stroop performance), and thus potentially increased interference from L1 phonotactic constraints. Further research is needed to examine the relations between different measures of linguistic and non-linguistic competition effects. Specifically, future studies may explore how the distinct components of competition, whether inhibition or facilitation, are involved in a domain-general way in bilinguals.

Conclusion

We examined the role of cognitive control abilities in suppressing activation of the irrelevant language during bilinguals’ relevant language comprehension. Performance on the non-linguistic Stroop arrows task was associated with phonotactic-constraint competition from the irrelevant language (Spanish) during comprehension. Competition resolution abilities related to the degree to which irrelevant-language phonotactic constraints were activated in bilinguals. It is thus likely that domain-general cognitive control mechanisms were recruited when bilinguals co-activated sublexical phonotactic constraints from the irrelevant language. The results have implications for understanding the extent to which cognitive control abilities relate to cross-linguistic sublexical competition in bilinguals.

Acknowledgements

We would like to thank members of the *Bilingualism and Psycholinguistics Research Group* at Northwestern University and the *Bilingualism & Cognition Lab* at San Diego State University.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Institute of Child Health and Human Development [grant number 1R01HD059858 to the third author].

References

Amengual, M. (2016). Cross-linguistic influence in the bilingual mental lexicon: Evidence of cognate effects in the phonetic production and processing of a vowel contrast. *Frontiers in Psychology*, *7*, 3099. doi:10.3389/fpsyg.2016.00617

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859–873. doi:10.1037/0278-7393.34.4.859

Bialystok, E., Martin, M. M., & Viswanathan, M. (2005). Bilingualism across the lifespan: The rise and fall of inhibitory control. *International Journal of Bilingualism*, *9*(1), 103–119. doi:10.1177/13670069050090010701

Blumenfeld, H. K., Bobb, S. C., & Marian, V. (2016). The role of language proficiency, cognate status and word frequency in the assessment of spanish–English bilinguals' verbal fluency. *International Journal of Speech-Language Pathology*, *18*(2), 190–201. doi:10.3109/17549507.2015.1081288

Blumenfeld, H. K., & Marian, V. (2007). Constraints on parallel activation in bilingual spoken language processing: Examining proficiency and lexical status using eye-tracking. *Language and Cognitive Processes*, *22*(5), 633–660. doi:10.1080/01690960601000746

Blumenfeld, H. K., & Marian, V. (2011). Bilingualism influences inhibitory control in auditory comprehension. *Cognition*, *118*(2), 245–257. doi:10.1016/j.cognition.2010.10.012

Blumenfeld, H. K., & Marian, V. (2013). Parallel language activation and cognitive control during spoken word recognition in bilinguals. *Journal of Cognitive Psychology*, *25*(5), 547–567. doi:10.1080/20445911.2013.812093

Blumenfeld, H. K., & Marian, V. (2014). Cognitive control in bilinguals: Advantages in stimulus–stimulus inhibition. *Bilingualism: Language and Cognition*, *17*(3), 610–629. doi:10.1017/S1366728913000564

Blumenfeld, H. K., Schroeder, S. R., Bobb, S. C., Freeman, M. R., & Marian, V. (2016). Auditory word recognition across the lifespan: Links between linguistic and non linguistic inhibitory control in bilinguals and monolinguals. *Linguistic Approaches to Bilingualism*, *6*(1), 119–146. doi:10.1075/lab.14030.blu

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436. doi:10.1163/156856897X00357

Broersma, M., & Cutler, A. (2011). Competition dynamics of second-language listening. *The Quarterly Journal of Experimental Psychology*, *64*(1), 74–95. doi:10.1080/17470218.2010.499174

Carlson, M. T., Goldrick, M., Blasingame, M., & Fink, A. (2016). Navigating conflicting phonotactic constraints in bilingual speech perception. *Bilingualism: Language and Cognition*, *19*, 939–954. doi:10.1017/S1366728915000334

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event related brain potential study. *Brain Research*, *1147*, 192–208. doi:10.1016/j.brainres.2007.01.137

Costa, A., Caramazza, A., & Sebastian-Galles, N. (2000). The cognate facilitation effect: Implications for models of lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1283–1296. doi:10.1037/0278-7393.26.5.1283

Dijkstra, T., & Van Heuven, W. J. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition*, *5*(3), 175–197. doi:10.1017/S1366728902003012

Durlik, J., Szewczyk, J., Muszyński, M., & Wodniecka, Z. (2016). Interference and inhibition in bilingual language comprehension: Evidence from Polish-English interlingual homographs. *PloS One*, *11*(3), e0151430. doi:10.1371/journal.pone.0151430

Freeman, M. R., Blumenfeld, H. K., & Marian, V. (2016). Phonotactic constraints are activated across languages in bilinguals. *Frontiers in Psychology*, *7*(702), 1–12. doi:10.3389/fpsyg.2016.00702

Freeman, M. R., Shook, A., & Marian, V. (2016). Cognitive and emotional effects of bilingualism in adulthood. In E. Nicoladis, & S. Montanari (Eds.), *Lifespan perspectives on bilingualism* (pp. 285–303). Berlin: APA and De Gruyter.

Giezen, M. R., Blumenfeld, H. K., Shook, A., Marian, V., & Emmorey, K. (2015). Parallel language activation and inhibitory control in bimodal bilinguals. *Cognition*, *141*, 9–25. doi:10.1016/j.cognition.2015.04.009

Goldrick, M., Runnqvist, E., & Costa, A. (2014). Language switching makes pronunciation less nativelike. *Psychological Science*, *25*(4), 1031–1036. doi:10.1177/0956797613520014

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

Hoshino, N., & Kroll, J. F. (2008). Cognate effects in picture naming: Does cross-language activation survive a change of script? *Cognition*, *106*(1), 501–511. doi:10.1016/j.cognition.2007.02.001

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, *59*, 434–446. doi:10.1016/j.jml .2007.11.007

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception 36*. ECVP Abstract Supplement.

Kornblum, S., Stevens, G., Whipple, A., & Requin, J. (1999). The effects of irrelevant stimuli: 1. The time course of stimulus–stimulus and stimulus–response consistency effects with stroop-like stimuli, simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 688–714. doi:10.1037/0096-1523.25.3.688

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology*, *25*(5), 497–514. doi:10.1080/20445911.2013.799170

Kroll, J. F., Bobb, S. C., Misra, M., & Guo, T. (2008). Language selection in bilingual speech: Evidence for inhibitory processes. *Acta Psychologica*, *128*(3), 416–430. doi:10.1016/j.actpsy.2008.02.001

Linck, J. A., Hoshino, N., & Kroll, J. F. (2008). L2 vocabulary: The interface between learning and representation. *The Mental Lexicon*, *3*(3), 349–374. doi:10.1075/ml.3.3.06lin

Linck, J. A., Schwieter, J. W., & Sunderman, G. (2012). Inhibitory control predicts language switching performance in trilingual speech production. *Bilingualism: Language and Cognition*, 1–12. doi:10.1017/S136672891100054X

Luk, G., de Sa, E., & Bialystok, E. (2011). Is there a relation between onset age of bilingualism and enhancement of cognitive control? *Bilingualism: Language and Cognition*, *14*(04), 588–595. doi:10.1017/S1366728911000010

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The language experience and proficiency questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech Language and Hearing Research*, *50*(4), 940–967. doi:10.1044/1092-4388(2007/067)

Martín, M. C., Macizo, P., & Bajo, T. (2010). Time course of inhibitory processes in bilingual language processing. *British Journal of Psychology*, *101*(4), 679–693. doi:10.1348/000712609X480571

Mercier, J., Pivneva, I., & Titone, D. (2014). Individual differences in inhibitory control relate to bilingual spoken word processing. *Bilingualism: Language and Cognition*, *17*(1), 89–117. doi:10.1017/S1366728913000084

National Institutes of Health Toolbox Cognition Battery (NIH Toolbox CB). (2013). *Monographs of the Society for Research in Child Development*, *78*(4), 1–15. doi:10.1111/mono.1203

Nip, I. S., & Blumenfeld, H. K. (2015). Proficiency and linguistic complexity influence speech motor control and performance in Spanish language learners. *Journal of Speech, Language, and Hearing Research*, *58*, 653–668. doi:10.1044/2015_JSLHR-S-13-0299

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442. doi:10.1163/156856897X00366

Prior, A., & Gollan, T. H. (2011). Good language-switchers are good task-switchers: Evidence from Spanish–English and Mandarin–English bilinguals. *Journal of the International Neuropsychological Society*, *17*(4), 682–691. doi:10.1017/S1355617711000580

PsychCorp. (1999). *Wechsler abbreviated scale of intelligence (WASI)*. San Antonio, TX: Harcourt Assessment.

Roelofs, A., & Verhoef, K. (2006). Modeling the control of phonological encoding in bilingual speakers. *Bilingualism: Language and Cognition*, *9*(2), 167–176. doi:10.1017/S1366728906002513

Shook, A., & Marian, V. (2013). The bilingual language interaction network for comprehension of speech. *Bilingualism: Language and Cognition*, *16*(2), 304–324. doi:10.1017/S1366728912000466

Tanenhaus, M., Spivey-Knowlton, M., Eberhard, K., & Sedivy, J. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, *268*, 1632–1634. doi:10.1126/science.7777863

Teubner-Rhodes, S. E., Mishler, A., Corbett, R., Andreu, L., Sanz-Torrent, M., Trueswell, J. C., & Novick, J. M. (2016). The effects of bilingualism on conflict monitoring, cognitive control, and garden-path recovery. *Cognition*, *150*, 213–231. doi:10.1016/j.cognition.2016.02.011

Weber, A., & Cutler, A. (2006). First-language phonotactics in second-language listening. *The Journal of the Acoustical Society of America*, *119*(1), 597–607. doi:10.1121/1.2141003

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001/2007). *Woodcock Johnson III tests of cognitive abilities*. Rolling Meadows, IL: Riverside.

Yavas, M., & Someillan, M. (2005). Patterns of acquisition of/s/-clusters in spanish-English bilinguals. *Journal of Multilingual Communication Disorders*, *3*(1), 50–55. doi:10.1080/14769670400018323