# ABSTRACT

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| Title of Document: | THE NEURAL BASES OF THE BILINGUAL ADVANTAGE IN COGNITIVE CONTROL: AN INVESTIGATION OF CONFLICT ADAPTATION PHENOMENA |
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The present dissertation examines the effects of bilingualism on cognitive control, the ability to regulate attention, particularly in the face of multiple, competing sources of information. Across four experiments, I assess the conflict monitoring theory of the so-called "bilingual advantage", which states that bilinguals are better than monolinguals at detecting conflict between multiple sources of information and flexibly recruiting cognitive control to resolve such competition. In Experiment 1, I show that conflict adaptation, the phenomenon that individuals get better at resolving conflict immediately after encountering conflict, occurs across domains, a pre-requisite to determining whether bilingualism can improve conflict monitoring on non-linguistic tasks. Experiments 2 and 3 compare behavioral and neural conflict adaptation effects in bilinguals and monolinguals. I find that bilinguals are more accurate at detecting initial conflicts and show corresponding increases in activation in neural regions implicated in language-switching. Finally, Experiment 4 extends the bilingual advantage in conflict monitoring to syntactic ambiguity resolution and recognition memory.

THE NEURAL BASES OF THE BILINGUAL ADVANTAGE IN COGNITIVE
CONTROL: AN INVESTIGATION OF CONFLICT ADAPTATION PHENOMENA.


By


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# Chapter 1: Introduction

*Overview of Cognitive Control*

   The physical world is rife with diverse stimuli in constant competition with one another. In order to make appropriate decisions in the face of such competition, individuals must direct their attention to goal-relevant input, ignore extraneous information, and resolve among conflicting alternatives. Take, for example, the case of American citizens trying to cross the street on a first visit to the United Kingdom, where the cars drive on the other side of the road. Having a lifetime of experience of looking left before stepping off of the sidewalk, they may persist in looking left despite their new environment. Thus, assuming that the travelers' goal is to avoid being run over, the habitual response conflicts with the contextually-appropriate response of looking in the direction of oncoming traffic. Individuals employ cognitive control, or the ability to regulate mental behavior, in order to resolve among conflicting alternatives and to override pre-potent responses[1], like the one in the previous example. The purpose of the present dissertation is to examine how cognitive control is shaped by experience by investigating how the experience of having to maintain and use two different languages (i.e., bilingualism) influences cognitive control abilities.

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[1] Whether the selection of the correct alternative is due to inhibition of irrelevant mental representations or to facilitation of the relevant representation is contested. This debate does not bear on the present studies, and will not be discussed further. Any references to selection via inhibition or facilitation are not meant as support for one or the other hypothesis, but merely as a convenient description of the process of conflict resolution.

Evidence demonstrates that individuals are better (e.g., faster and more accurate) at resolving a current conflict that was immediately preceded by another conflict than they are at resolving a current conflict that was not preceded by any conflict (Botvinick, Braver, Barch, Carter & Cohen, 2001; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Gratton, Coles, & Donchin, 1992; Ullsperger, Bylsma, & Botvinick, 2005). Such 'conflict adaptation' effects suggest that individuals may adjust the strength of cognitive control activity following the detection of conflict. Indeed, the prominent 'conflict monitoring' theory (Botvinick et al., 1999, 2001) proposes a system that is responsible for detecting conflict and signaling subsequent modifications in the recruitment of control; one consequence of this system is that, after encountering conflict, cognitive control will be boosted, resulting in enhanced conflict resolution on subsequent trials. Supporting evidence for a conflict monitoring system comes from studies investigating real-time modulations of neural activity: Botvinick and colleagues (1999) found that, during tasks with randomly interleaved conflict and non-conflict trials, the anterior cingulate cortex (ACC) shows greater activation for initial conflict trials (that were immediately preceded by a non-conflict trial) than for subsequent conflict trials (that were immediately preceded by a conflict trial), paralleling the behavioral conflict adaptation effect. Moreover, greater ACC activation on an initial conflict trial is associated with faster and more accurate responding for a subsequent conflict one trial later (Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004), suggesting that the ACC may be responsible for signaling the adjustments in cognitive control recruitment that lead to behavioral conflict adaptation. Indeed, increased ACC activity predicted increased activity one trial later in prefrontal cognitive control regions, particularly the dorsolateral

prefrontal cortex (dlPFC), indicating a functional relationship between a region responsible for detecting conflict and a region responsible for implementing cognitive control (Kerns et al., 2004). Such flexible, moment-by-moment adjustments in cognitive control can provide important insight into the mechanisms underlying real-world decision making. In particular, they may help to explain why some individuals seem to be better than others at conflict resolution.

*Review of the Bilingual Advantage*

Individuals vary widely in how effective they are at resolving between conflicting representations. One example that has recently garnered interest is that bilinguals outperform monolinguals on domain-general (e.g., linguistic and non-linguistic) tasks requiring cognitive control (Bialystok, 2010; Bialystok, Craik, Klein, & Viswanathan, 2004; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Martin-Rhee & Bialystok, 2008). This especially applies to balanced bilinguals, who, having been exposed to two languages from infancy or early childhood, are equally proficient in both. The so-called "bilingual advantage" is evident across the lifespan: young bilingual children outperform monolinguals on executive function tasks requiring inhibition and attention control (Bialystok, 1999, 2010; Bialystok & Martin, 2004; Kovács & Mehler, 2009; Martin-Rhee & Bialystok, 2008); healthy adult bilinguals are faster than monolinguals on cognitive control tasks (Bialystok, 2006; Costa et al., 2009; Costa, Hernández, & Sebastián-Gallés, 2008); and older adult bilinguals exhibit less cognitive decline due to aging than monolinguals (Bialystok et al., 2004) and are relatively protected against the early effects of Alzheimer's (Schweizer, Ware, Fischer, Craik, & Bialystok, 2012).

The precise reason for bilinguals' cognitive advantages is not known, but it is postulated that by perpetually switching between their languages, bilinguals essentially get extensive practice in selecting one representation (e.g., a word from one language) while inhibiting the other (e.g., a word from the other language); that is, they may be practicing (and improving) conflict resolution merely by using language! The inhibitory control (IC) model of bilingual language processing theorizes that bilinguals suppress items from the lexicon that they are not currently using via a central inhibitory-control mechanism (Green, 1998). For instance, bilinguals might inhibit words from their native language (L1) when speaking their second language (L2). Asymmetric language-switching costs provide evidence for such inhibition: specifically, switching from a weaker to a dominant language during picture-naming is harder than vice versa, demonstrating that individuals must actively suppress their dominant language in order to output their weaker one (Meuter & Allport, 1999). Thus, under the IC model, bilingualism could act as a naturalistic form of cognitive training, strengthening domain-general inhibitory control mechanisms (Abutalebi & Green, 2008; Bialystok, Craik, Green, & Gollan, 2009); bilinguals could then apply their improved inhibitory control to non-verbal tasks, yielding their observed advantage.

Under the IC account, bilinguals should outperform monolinguals selectively on trials that induce conflict, because bilinguals have practice with inhibiting irrelevant information. In a few cases, evidence for the bilingual advantage in cognitive control is consistent with this prediction. For example, Kovács and Mehler (2009) found that bilinguals as young as 7-months-old successfully inhibited looks to a previously rewarded—but now incorrect—location, whereas monolinguals did not. Interestingly,

since this population was pre-verbal, this suggests that the demands of bilingual language comprehension require inhibitory control as well. Additional support for the IC model comes from adult populations: compared to their monolingual peers, middle-aged and older bilinguals had a reduced interference effect (e.g., less impairment on incongruent trials relative to baseline congruent trial performance) on the Simon task, in which the correct response to a non-spatial attribute of a visual stimulus is on the same (congruent trials) or the opposite (incongruent trials) side as the stimulus location (Bialystok, Craik, Klein, & Viswanathan, 2004). Interestingly, this effect only reached significance in older adults, suggesting that if there is a bilingual advantage in inhibitory control, it is more evident in populations in which this ability is naturally reduced (e.g., older adults and young children). It is important to note, however, that in the middle-aged adults, bilinguals were faster than monolinguals on both congruent and incongruent trials; while this younger population of bilinguals did not demonstrate an advantage in inhibitory control, they still demonstrated an overall advantage on the Simon task.

Based on evidence that bilinguals typically outperform monolinguals on both congruent and incongruent trials without exhibiting reduced interference effects, researchers have proposed an alternative account of the bilingual advantage, which suggests that it stems from superior conflict monitoring (Costa et al., 2009; Hilchey & Klein, 2011). During conflict monitoring, individuals continuously evaluate input to determine if it contains conflicting sources of information. If so, then cognitive control is recruited to help resolve the competing evidence; otherwise, cognitive control need not be deployed (Botvinick et al., 2001). If bilinguals are better at conflict monitoring, then they should outperform monolinguals on both congruent and incongruent trials, because

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they must decide (albeit unconsciously) whether or not to recruit cognitive control, regardless of trial type. However, a bilingual advantage would only be expected when conflict monitoring demands are high, namely, when the input frequently switches between stimuli with and without conflict, and people must decide to recruit cognitive control on a moment-by-moment basis. In contrast, a bilingual advantage would not be expected in low monitoring contexts where conflict is nearly always present; in such environments, individuals can apply cognitive control consistently without monitoring.

Because the conflict monitoring account of the bilingual advantage is relatively recent, there are only a handful of studies explicitly testing its predictions. Notably, Costa et al. (2009) observed that the magnitude of the bilingual advantage was modulated by the degree of switching between congruent and incongruent trials on a Flanker task, in which participants identified a target stimulus which was surrounded, or 'flanked', by identical (congruent) or opposing (incongruent) distracter stimuli. When switching occurred frequently, imposing the need to monitor for conflict and adjust cognitive control accordingly, bilinguals were significantly faster at both trial types, but when very little switching occurred, even if the majority of trials were incongruent, bilinguals performed no differently from monolinguals (Costa et al., 2009). More recent evidence has shown that language-switching during a picture-naming task activates the same voxels as Flanker conflict in the ACC (Abutalebi et al., 2012), the structure thought to be responsible for detecting conflict and signaling adjustments in control. This finding confirms that language-switching recruits the same neural resources as general conflict processing, making language-switching a plausible mechanism for improving cognitive control abilities. Moreover, this evidence supports the conflict monitoring theory of the

bilingual advantage because language-switching and conflict co-activated the ACC, a region that is integral to the neural conflict monitoring system. Additional evidence for the role of the ACC in the bilingual advantage comes from differences in task-switching performance between older adult bilinguals and monolinguals. Relative to monolinguals, bilinguals demonstrated reduced switch-costs in a color-shape decision task where participants alternated between identifying the color and identifying the shape of a picture (Gold, Kim, Johnson, Kryscio, & Smith, 2013). Moreover, this performance boost was accompanied by reduced activation of regions in the conflict monitoring network (Gold et al., 2013), including the ACC, the left dorsolateral prefrontal cortex (dlPFC), and the left ventrolateral prefrontal cortex (vlPFC). That bilinguals exhibit better switching performance while simultaneously engaging to a lesser extent the neural resources involved in conflict detection (ACC) and resolution (dlPFC and vlPFC) suggests that their conflict monitoring system is more efficient as a result of extensive practice with language-switching.

*Rationale for the Present Studies*

Despite recent evidence that the bilingual advantage may stem from improved conflict monitoring abilities, no study to date has compared conflict adaptation effects in bilinguals and monolinguals. Conflict adaptation is the behavioral hallmark of the conflict monitoring system, because it reveals trial-by-trial adjustments in the engagement of cognitive control following the occurrence of conflict. Specifically, conflict adaptation seems to occur because individuals flexibly increase their recruitment of cognitive control after detecting conflict, resulting in stronger cognitive control when facing subsequent conflicts, and ultimately leading to better performance on subsequent

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conflict trials (Botvinick et al., 2001). This interpretation of conflict adaptation is supported by corresponding neural activation: recall that greater activity in the ACC during conflict detection is associated with greater activity in the dlPFC one trial later, suggesting that recruitment of cognitive control resources is increased following conflict detection. If the bilingual advantage indeed reflects better conflict monitoring, then bilinguals should outperform monolinguals in one of the two stages of conflict monitoring that are related to conflict adaptation effects: they should exhibit either superior conflict detection or increased reactive recruitment of cognitive control. Any behavioral advantages in conflict adaptation should be accompanied by changes in activation in the neural conflict monitoring network, namely, the ACC, the vlPFC, and the dlPFC, but also in regions outside the traditional monitoring network that are recruited by bilinguals during language control. For instance, when bilinguals flexibly shift between their languages during comprehension or production, they may be strengthening resources involved in language-switching. If these language-switching resources are enhanced, then it would be beneficial for bilinguals to co-opt them for general purpose conflict monitoring.

Another issue undermining the current evidence for the bilingual advantage is that bilingualism's effects on cognitive control have been primarily examined using non-linguistic tasks. If controlled use of two languages enhances cognitive control, then bilingualism must necessarily impact linguistic cognitive control performance as well. However, it has been traditionally difficult to examine the effects of bilingualism on cognitive control in linguistic domains because, by virtue of having to learn and maintain two languages, bilinguals typically exhibit smaller single-

language vocabularies (Bialystok & Feng, 2009; 2011; Portocarrero, Burright, & Donovick, 2007) and slower lexical access relative to monolinguals (Ivanova & Costa, 2008; Sandoval, Gollan, & Ferreira, 2010). However, psycholinguistic and neurolinguistic evidence (January, Trueswell, & Thompson-Schill, 2009; Novick, Kan, Trueswell, & Thompson-Schill, 2009; Novick, Truewsell, & Thompson-Schill, 2005) suggests that certain types of language processing require cognitive control; in particular, cognitive control may be deployed to resolve competition when language requires selection among competing alternatives, either in production (e.g., selection between categorical exemplars on a verbal fluency task) or comprehension (e.g., selection between a favored initial parse and the correct, syntactically-licensed parse during sentence processing). Thus, despite falling behind their monolingual peers in some linguistic measures, bilinguals should still enjoy an advantage in sentence processing when cognitive control demands are high—namely, when the linguistic context necessitates monitoring for syntactic conflict and potentially frequent misinterpretation.

The goal of the present dissertation was to evaluate the conflict monitoring theory of the bilingual advantage, particularly by comparing behavioral and neural conflict adaptation effects in bilinguals and monolinguals and by investigating whether the advantage manifests in sentence processing involving occasional syntactic conflict. Experiment 1 assesses whether behavioral conflict adaptation genuinely reflects recruitment of domain-general cognitive control to verify that it is a sensible marker of conflict monitoring. Experiment 2 investigates behavioral conflict adaptation effects in bilinguals and monolinguals to determine whether bilinguals exhibit an advantage in

either conflict detection or reactive adjustments in cognitive control. Experiment 3 uses

fMRI to examine how the experience of bilingualism affects the neural system underlying

conflict adaptation effects. Finally, Experiment 4 tests whether bilinguals are better than

monolinguals at sentence parsing and comprehension in a linguistic context that requires

monitoring for syntactic conflict.

# Chapter 2: Experiment 1[2]

*Overview*

The hypothesis that bilingualism should influence conflict adaptation effects is predicated on the assumption that conflict adaptation occurs because encountering conflict activates cognitive control mechanisms that persist onto subsequent conflict trials. Moreover, for these mechanisms to be the ones responsible for the bilingual advantage, they must be domain-general, operating in both linguistic and non-linguistic cognitive control tasks. Both of these assumptions are controversial: many authors (Mayr & Awh, 2009; Mayr, Awh, & Laurey, 2003; Nieuwenhuis, Stins, Posthuma, Polderman, Boomsma, & De Geus, 2006) have suggested that conflict adaptation is an artifact of stimulus repetitions, which are more likely to occur if adjacent stimuli are presented from the same conflict condition; others argue that, though conflict adaptation *is* the result of adjustments in cognitive control, this control operates only within a single domain (Akçay & Hazeltine, 2008; Akçay & Hazeltine, 2011; Egner, Delano, & Hirsch, 2007). Thus, before the conflict adaptation paradigm can be used to investigate the conflict monitoring account of bilingual cognitive advantages, it must be demonstrated that conflict adaptation is the result of online adjustments in cognitive control rather than repetition priming and that conflict adaptation occurs across domains. The goal of Experiment 1 in the present dissertation was to test these assumptions of conflict

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adaptation by investigating whether conflict adaptation occurs across two different tasks from ostensibly different domains with entirely separate stimulus and response sets.

Recent work suggests that, whenever syntax is temporarily ambiguous between multiple plausible interpretations, sentence processing engages the same cognitive control resources that underlie conflict resolution on non-syntactic control tasks (Novick, Trueswell, Thompson-Schill, 2005). Thus, syntactic parsing may not solely involve syntactic mechanisms, but may also rely on more general cognitive control abilities. Take, for example, the NY times headline, "Google's computer might betters translation tool" (example from Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2013). The most common usage of the word "might" is as an auxiliary verb, meaning "may be"; readers thus temporarily assign the auxiliary verb meaning to the word "might" in this sentence, even though it is actually being used as a noun meaning "power." Psycholinguistic evidence reveals that individuals employ cognitive control to suppress their initial misinterpretation and recover the intended meaning when reading sentences like this one.

Supporting evidence for the role of cognitive control in syntactic ambiguity resolution comes from patients with prefrontal lesions and from neuroimaging studies. Novick, Kan, Trueswell, and Thompson-Schill (2009) tested a patient with focal damage to the left vlPFC on a variety of cognitive control tasks, including a non-syntactic recent-probes memory task and a syntactic ambiguity comprehension task. They found that, across the tasks, the patient was selectively impaired on trials that involved conflict resolution. Namely, the patient exhibited exaggerated error rates on proactive-interference memory trials, which required overriding a familiarity response to a recently

presented but currently irrelevant item, and also committed frequent overt errors on the syntactic ambiguity task, indicating failure to revise his initial interpretation. The co-occurrence of these deficits suggests that the left vlPFC underlies both syntactic and non-syntactic conflict resolution. Moreover, evidence from fMRI indicates that overlapping voxels in the vlPFC are co-activated *within individuals* by conflict on the Stroop task (defined as incongruent trials for which the meaning of a color word does not match the font color of that word) and by syntactic ambiguity (January, Trueswell, & Thompson-Schill, 2009). This finding indicates that the vlPFC is involved in both domain-general cognitive control and syntactic ambiguity resolution in healthy adults, not just in patient populations.

Although prior research demonstrates that syntactic ambiguity resolution requires the same conflict resolution mechanisms used in domain-general cognitive control tasks, like Stroop, no study has investigated whether syntactic ambiguity can induce conflict adaptation, which would demonstrate that the conflict monitoring system is domain-general. This is a pre-requisite to examining the conflict monitoring theory of the bilingual advantage, because the bilingual advantage itself appears to be domain-general. Specifically, because the advantage apparently stems from the systematic control of two languages but emerges on non-linguistic cognitive control tasks (Bialystok, 2010; Bialystok et al., 2004; Bialystok & Viswanathan, 2009; Costa et al., 2008; 2009; Hernández et al., 2010), the advantage must be tapping a mechanism that spans linguistic and non-linguistic domains.

If syntactic ambiguity indeed activates domain-general cognitive control resources, then it should also lead to better performance on subsequent conflict trials. In

order to test whether conflict adaptation can occur across domains, Experiment 1 interleaved stimuli from a traditional cognitive control task, the Stroop task, with syntactically ambiguous (and unambiguous) sentences. In the Stroop task (Stroop, 1935), participants must name the font color of words which are themselves names of colors. On non-conflict or congruent trials, the font color and the word meaning match each other, so the word meaning, though irrelevant to the task goal of naming the font color, still facilitates color naming. In contrast, on conflict or incongruent trials, the font color and the word meaning mismatch, leading to two possible yet incompatible responses—this conflict must be resolved, either by inhibiting the irrelevant word meaning or enhancing activation of the goal-relevant font color, in order for the participant to output the correct response. The occurrence of conflict adaptation during the Stroop task, where participants are faster and more accurate on incongruent trials that were preceded by incongruent trials than on incongruent trials that were preceded by congruent trials, has been widely replicated (Botvinick, Cohen, & Carter, 2004; Jiménez & Méndez, 2013; Kerns et al., 2004; Larson, Kaufman, & Perlstein, 2009).

The purpose of interleaving a sentence processing task with the Stroop task is two-fold: 1) Because the tasks contain separate stimuli and response sets, this design completely removes stimulus repetitions from the task, so that any observed conflict adaptation cannot be attributed to repetition priming. Thus, finding conflict adaptation in this paradigm would ensure that adaptation is due to online adjustments in cognitive control; 2) It further probes the theory that syntactic ambiguity resolution relies on domain-general cognitive control mechanisms. Conflict adaptation should only occur from a syntactic ambiguity task to a Stroop task if both tasks are engaging the same

neural resources. Despite their apparently dissimilar task structures, I hypothesize that, because they purportedly share cognitive control demands, syntactic ambiguity and the Stroop task should elicit conflict adaptation that generalizes from one task to the other. Such a finding would pose a significant challenge to repetition priming accounts of conflict adaptation and provide strong evidence for domain-general cognitive control. It would also support the notion that encountering competition between two languages could engage and strengthen a domain-general conflict monitoring system, leading to the observed bilingual advantage. Moreover, it would suggest that, because syntactic ambiguity and non-syntactic conflicts tap the same conflict monitoring system, a bilingual advantage in conflict monitoring should extend to syntactic ambiguity resolution (see Chapter 5).

*Method*

All subjects performed a standard color-word Stroop task and a sentence processing task (hereafter, the Stroop-Sentence task), which were interleaved so that each trial could be followed by either a Stroop trial or a sentence trial. Both tasks included conflict trials (incongruent Stroop trials or ambiguous sentences) and non-conflict trials (congruent Stroop trials or unambiguous sentences) in order to assess conflict adaptation. For the purpose of using consistent terminology across tasks when referencing trial type, conflict trials on both tasks are referred to as incongruent, whereas non-conflict trials on both tasks are referred to as congruent. These trials were pseudorandomized to produce equal numbers of four conflict adaptation conditions: congruent trials preceded by congruent trials (CC); incongruent trials

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preceded by congruent trials (CI); congruent trials preceded by incongruent trials (IC); and incongruent trials preceded by incongruent trials (II). Thus, the condition of a particular trial was given by both the current trial type *and* the preceding trial type, where the first letter indicates the preceding trial type and the second letter the current trial type. I was primarily interested in cross-task adaptation, because within-task conflict adaptation does not inform the question of whether conflict adaptation reflects engagement of domain-general cognitive control; therefore, the trials were arranged to maximize cross-task conflict adaptation sequences, and within-task sequences were included only to minimize predictability of task type.

Participants

All subjects (N = 41) were undergraduates at Villanova University. After undergoing informed consent, each subject was tested individually. Each session lasted approximately 45 minutes, and subjects received course credit for their participation.

Materials

The Stroop-Sentence task consisted of 191 trials, of which 71 were sentences (21 ambiguous, 21 unambiguous and 29 filler) and 120 were Stroop trials (60 congruent and 60 incongruent). On color-word Stroop trials, subjects identified the ink color (blue, yellow, or green) in which color names were printed, responding as quickly and accurately as possible via button press. Whereas color names matched the ink colors on congruent trials (e.g., the word "blue" printed in blue ink), color names and ink colors were mismatched on incongruent trials (e.g., the word "red" printed in blue ink). Because syntactic ambiguity is believed to involve representational

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conflict (Novick et al., 2005), or competition between incompatible interpretations, I used a "response-ineligible" version of the Stroop task that was designed to involve only representational conflict without also involving conflict between competing response options (see e.g., January et al., 2009; Milham, Banich, & Barad, 2003; Milham et al., 2001). Specifically, on incongruent trials, the written color names were not among the possible response options, but were other, response-ineligible color names ("red", "brown", and "orange"). Since participants' button response options were blue, yellow and green, and they never saw a word printed in red, brown, or orange, the word meaning could not lead to a competing response on these trials. Thus, the incongruent trials induced a *meaning-based* conflict between the mental representation of the written color name and the ink color, but did not induce a *response-based* conflict because there was no button press corresponding to the written color name. Previous research has found that the interference effect is reduced for response-ineligible incongruent trials relative to traditional response-eligible incongruent trials, supporting the notion that they do not involve response conflict (January et al., 2009; Milham, Banich, & Barad, 2003; Milham et al., 2001).

On sentence trials, participants read the sentences by pressing the spacebar to reveal the sentence one word at a time (e.g., self-paced reading). Sentences were either syntactically unambiguous (congruent) or they contained a temporary syntactic ambiguity (incongruent). Ambiguous sentences cause temporary misinterpretation that requires subsequent revision by the reader, a process that engages domain-general cognitive control (Novick et al., 2005; Novick et al., 2009; Ye & Zhou,

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2009). Unambiguous sentences do not cause such misinterpretation and consequently, cognitive control does not need to be deployed to recover the intended meaning.

All sentences were based on materials from Garnsey, Pearlmutter, Myers and Lotocky (1997). Each experimental (e.g., non-filler) sentence contained a verb that was biased to take a direct-object (e.g., "accept"), but instead was followed by a sentence complement (see (a) and (b)). For example:

(a) The basketball player accepted the contract would have to be negotiated. (Temporarily Ambiguous)

(b) The basketball player accepted *that* the contract would have to be negotiated. (Unambiguous)

In (a), the verb "accept" is immediately followed by a plausible direct object "the contract", such that both the preferred (but incorrect) direct-object interpretation and the dispreferred (but correct) sentence-complement interpretation of "the contract" are temporarily viable. Readers briefly misinterpret these sentences (e.g., Garnsey et al., 1997; Novick, Thompson-Schill, & Trueswell, 2008) because the reader generates verb-based predictions, which ultimately conflict with the current syntactic context. For instance, the verb "accept" is typically followed by a direct-object, so readers expect a direct-object; when they encounter evidence that conflicts with this expectation, like "would have," they slow down (Garnsey et al., 1997). This suggests that, at first, readers mischaracterize "the contract" as a direct object ("The basketball player accepted the contract…") but then revise that analysis and recover the correct complement-clause interpretation ("…the contract would have to be negotiated"). Critically, adding the word "that" in (b) syntactically cues the complement-clause

reading, thus blocking the incorrect direct object interpretation and reducing processing difficulty (Ferreira & Henderson, 1990; Trueswell, Tanenhaus, & Kello, 1993). Therefore, in ambiguous sentences, but not unambiguous sentences, readers must overcome their initial direct-object bias in order to arrive at the correct parse. In our study, ambiguous sentences are equivalent to incongruent Stroop trials, in that both require conflict resolution between two competing representations.

Stroop and sentence trials were pseudorandomized with the constraint that experimental sentences were always preceded and followed by a Stroop trial. To ensure that participants could not detect this pattern, filler sentences, which had different constructions than the experimental sentences, were adjacent to either filler sentences or Stroop trials, and Stroop trials were adjacent to either sentence trials or Stroop trials. There were two types of cross-task trials: Stroop trials preceded by sentence trials (Sent-Stroop) and sentence trials preceded by Stroop trials (Stroop-Sent). Both of these cross-task trial types contained 10 trials of each of the four critical conflict adaptation conditions (CC, CI, IC, II).[3] The remaining trials did not fall into one of the cross-task conflict adaptation conditions, either because they were preceded by a trial from the same task, or because they were preceded by a filler sentence.

To ensure that subjects read the sentences, subjects answered true/false comprehension probes after 10 of the filler sentences. Probe questions were not included after the experimental sentences because introducing such items before a Stroop trial could disrupt the sustained engagement of cognitive control across tasks.

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[3] Due to sequencing constraints, there was one additional CC trial of the Stroop-Sent type.

Probe questions were included after only a subset of the filler sentences to prevent them from drawing the participants' attention towards the experimental manipulation.

Procedure

Prior to the mixed Stroop-Sentence task, participants practiced trials from each task to familiarize themselves with task procedures. First, they were given 10 Stroop trials in order to learn the color response mappings, followed by a baseline block of 145 Stroop trials. Then, they read a sample filler sentence to acquaint themselves with the self-paced moving-window procedure. Before continuing onto the experiment, participants completed 20 intermixed Stroop-Sentence practice trials, in order to become accustomed to switching between trial types. This mixed-task practice session followed the same procedure as the main experiment, except that none of the sentences contained the ambiguous or unambiguous construction of the experimental items.

In the mixed-task experiment, each trial began with a left-aligned fixation cross, which was replaced by either a Stroop or sentence stimulus after 500 ms. The Stroop stimulus remained on the screen for 1000 ms, and was followed by a blank screen for an additional 1000 ms, before the fixation cross for the next trial appeared. The sentence stimulus began with a full mask (i.e., a string of dashes that corresponded to the number of letters and words in the sentence in place of actual words) until the subject pressed the space bar to begin reading one word at a time. After the subject read the last word in the sentence, a blank screen appeared for 1000 ms.  For the subset of filler sentences with comprehension probes, the blank screen was followed by a true/false statement, which remained on the screen until the subject

responded. After the participant responded, the screen was blank for 1500 ms before the start of the next trial.

*Results*

One subject was excluded from all analyses for failing to complete the experiment. To ensure that subjects were actually reading the sentences, accuracy was analyzed in response to comprehension questions, using 70% correct[4] (7 out of 10 questions) as the cut-off threshold. One participant whose performance fell below this threshold (to 50%) was excluded from subsequent analyses. The remaining participants (n = 39) all scored 70% or above on sentence comprehension (*M* = .9, *SD* = .09). Due to a programming error, one of the congruent sentence trials was missing the last word for half of the participants (n = 19). For these subjects, both the sentence trial and the subsequent Stroop trial (CI) were removed from all analyses.

Analyses focused on the influence of sentences on Stroop trial accuracy and reaction time (RT), because Stroop is known to produce robust interference and conflict adaptation effects (Botvinick, Cohen, & Carter, 2004; Jiménez & Méndez, 2013; Kerns et al., 2004; Larson, Kaufman, & Perlstein, 2009). A typically used index of conflict adaptation is the interaction between preceding trial type and current trial type. A significant interaction term reflects that interference effects (e.g., more errors or longer reaction times for incongruent relative to congruent trials) on the current trial are contingent on the preceding trial type. In this case, it would reveal that the effect of congruency on the current Stroop trial depends on the congruency of

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[4] This threshold is slightly lower than the 75% threshold used in later experiments. This was necessarily the case, because Experiment 1 included only 10 comprehension questions, so it was not possible to achieve an accuracy of 75%.

the preceding sentence trial. Thus, data were submitted to a 2 x 2 (preceding trial x current trial type) repeated-measures ANOVA for both accuracy and reaction time (RT), including only those critical Stroop trials that were preceded by sentence trials.

For the accuracy data, neither the main effect of preceding trial type ($F(1, 38)$ = 2.17, $p$ = .15), nor the main effect of current trial type was significant ($F(1, 38)$ = 2.27, $p$ = .14). There was, however, a significant interaction between preceding trial type and current trial type ($F(1, 38)$ = 6.22, $p$ = .02), indicating that the effect of the current Stroop trial congruency was modified by preceding sentence trial congruency. To further investigate this interaction, pairwise comparisons between the conditions of interest were conducted using two-tailed paired t-tests at the Bonferroni-corrected alpha level of .025. For completeness, Bayes Factors (BF) were also computed with the Unit-Information prior using the online BF calculators developed by Rouder, Speckman, Sun, Morey, and Iverson (2009). Following the example of Wetzels et al. (2011), BFs are stated as the odds in favor of the alternative hypothesis relative to the null (as opposed to the inverse employed by Rouder et al., 2009). Thus, BFs < 1 are evidence for the null and BFs > 1 are evidence for the alternative, such that BFs > 3 are considered substantial, BFs > 10 strong, and BFs > 30 very strong support for the alternative (Wetzels et al., 2011).

Stroop interference effects (e.g., decreased accuracy on incongruent relative to congruent trials) were assessed while controlling preceding trial type by comparing CC to CI performance and by comparing IC to II performance. As can be seen in Table 1, although participants were numerically less accurate on CI than II trials, the interference effect was not significant when the preceding sentence trial was

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congruent ($t(38) = 2.243$, $p = .03$; BF = 1.67) nor when the preceding sentence trial

was incongruent ($t(38) = -0.26$, $p = .8$; BF = 0.16). However, if participants exhibit

lower accuracy on CI trials relative to II trials while exhibiting equivalent accuracy

on CC and IC trials, this would still indicate adaptation to conflict following an

incongruent sentence trial. Indeed, participants were significantly less accurate on CI

than on II trials ($t(38) = -2.534$, $p = .016$; BF = 3.06), but performance was not

significantly different between CC and IC trials ($t(38) = 0.467$, $p = .64$; BF = 0.18).

This reveals that the numerically reduced interference effect following incongruent

trials is the result of higher accuracy on II trials relative to CI trials, suggesting that

participants exhibited conflict adaptation on Stroop trials that followed ambiguous

sentences.

Table 1

*Accuracy and Reaction Time on Stroop Trials by Preceding Sentence Type*

| Measure | Preceding Congruent | | Preceding Incongruent | |
|---------|------|------|------|------|
|         | CC   | CI   | IC   | II   |
| *Proportion Correct* | | | | |
| *M*     | .97  | .94  | .97  | .97  |
| *SD*    | .04  | .09  | .06  | .07  |
| *Reaction Time* | | | | |
| *M*     | 672.76 | 715.88 | 685.12 | 698.46 |
| *SD*    | 101.35 | 84.80  | 105.33 | 86.09  |

The effects of preceding and current trial type on RT were analyzed for

correct trials only, because incorrect trials do not reflect successful conflict

resolution. Note that preceding trial accuracy was not controlled, because

participants' response to sentence trials was neither correct nor incorrect (they merely

responded to reveal the next word). To reduce the influence of outliers, I found all

trials with RTs that were more than 2.5 standard deviations away from the mean for each subject, and re-set the RT for those trials to the 2.5 standard deviation threshold value.

The 2 x 2 repeated-measures ANOVA of RTs revealed a significant main effect of current trial congruency ($F(1, 38) = 25.09$, $p < .0001$), but no effect of preceding trial congruency ($F(1, 38) = 0.21$, $p = .65$). Again, there was a significant interaction between preceding and current trial type ($F(1, 38) = 10.26$, $p = .003$). This interaction was explored in the same manner as the accuracy data, by examining the Stroop interference effects (e.g., RTs are slower on incongruent than on congruent trials) when the preceding trial was congruent and when the preceding trial was incongruent using paired two-tailed t-tests, using a Bonferroni-corrected alpha of .025. As shown in Table 1, RTs were significantly faster for CC than for CI trials, indicating a significant interference effect when the preceding sentence trial was congruent ($t(38) = -5.87$, $p < .0001$; BF > 1,000). In contrast, RTs were not significantly faster for IC than for II trials ($t(38) = -1.84$, $p = .07$; BF = 0.80). This pattern suggests that the interference effect was reduced when the preceding sentence trial was incongruent. Additional pairwise comparisons were conducted using a Bonferroni-corrected alpha of .025 to probe whether the different interference magnitudes were the result of faster responses on II trials relative to CI trials (the critical conflict adaptation comparison) or slower responses on IC trials relative to CC trials. Participants were significantly slower to respond on CI trials than II trials ($t(38) = 2.81$, $p < .008$; BF = 5.67), suggesting that they indeed exhibited conflict adaptation following sentence trials. Additionally, performance on IC trials was not significantly

different from performance on CC trials ($t(38) = 1.53$, $p = .13$; BF = 0.49), so the reduced interference following incongruent sentences cannot be attributed to slower responding on IC trials.

*Discussion*

The results from Experiment 1 demonstrated that conflict adaptation occurs across two apparently different tasks, transferring from a sentence processing task to a non-syntactic Stroop task. Because conflict adaptation occurred across two tasks with non-overlapping stimulus and response sets, these results render the repetition priming account of conflict adaptation (Mayr & Awh, 2009; Mayr et al., 2003; Nieuwenhuis et al., 2006) virtually untenable—conflict adaptation still occurred when stimulus repetitions were impossible. Instead, these findings support the conflict monitoring theory of conflict adaptation (Botvinick et al., 2001), namely, that conflict detection signals adjustments in cognitive control resources. These adjustments facilitate resolution during subsequent encounters with conflict because increased cognitive control engagement is sustained across trials. Such conflict adaptation could not occur across two different tasks unless both tasks engage shared cognitive resources. Thus, Experiment 1 provides further evidence that syntactic ambiguity resolution relies on domain-general cognitive control resources, the same as those used for conflict resolution in the Stroop task.

However, one legitimate concern about this interpretation of the results from Experiment 1 is that both the sentence-processing task and the Stroop task, though involving different stimuli types and task demands, are verbal in nature. The Stoop

task may not involve syntactic processing, but it certainly involves lexical processing, as its stimuli are all lexical items (e.g., color words). Thus, even though conflict adaptation occurred across syntactic and non-syntactic domains, this cross-task adaptation could be interpreted as adaptation *within* the more broadly-construed verbal domain. Perhaps these results were simply due to syntactic ambiguity and Stroop conflict tapping a verbal-specific cognitive control mechanism.

This limitation was addressed in the second experiment conducted by Kan, Teubner-Rhodes, Drummey, Nutile, Krupa and Novick (2013), not included in the present dissertation. This second experiment investigated conflict adaptation from a non-verbal perceptual ambiguity task involving passive-viewing of the Necker cube figure (Necker, 1832) to the color-word Stroop task. Participants viewed ambiguous and unambiguous versions of the Necker cube figure interleaved with incongruent and congruent Stroop stimuli. The ambiguous Necker cube is a figure with transparent, overlapping 2-dimensional squares, which can be perceived as one of two different shapes: a 3-dimensional rectangle pointing down and to the right or a 3-dimensional rectangle pointing up and to the left. The unambiguous version of the Necker cube is a figure with opaque, overlapping 3-dimensional squares, which can only be perceived as one 3-dimensional rectangular shape. Results showed that individuals who, on average, experienced a high number of reversals while viewing the ambiguous Necker cube were significantly more accurate on incongruent Stroop trials that were preceded by the ambiguous Necker figure than the unambiguous Necker figure (Kan, Teubner-Rhodes, Drummey, Nutile, Krupa, & Novick, 2013). In contrast, for individuals experiencing a low number of reversals, the preceding

Necker trial type did not influence accuracy on incongruent Stroop trials. Indeed, the average number of reversals experienced during passive viewing of the ambiguous Necker cube was significantly positively correlated with the extent of conflict adaptation, such that experiencing more reversals was associated with higher accuracy on II trials relative to CI trials (Kan, Teubner-Rhodes, Drummey, Nutile, Krupa, & Novick, 2013). Not only does this result demonstrate that conflict adaptation can occur across perceptual and verbal domains, but it also reveals that the amount of adaptation to conflict is directly related to the amount of ambiguity or conflict experienced, as would be expected if adaptation occurs as a reactive adjustment in cognitive control in response to the detection of conflict.

The results of Experiment 1 in conjunction with other cross-task conflict adaptation studies provide crucial evidence for domain-general cognitive control. Additionally, they support the theory that there is a domain-general system responsible for signaling adjustments in cognitive control and that this "conflict monitoring" system underlies conflict adaptation, via the sustained engagement of cognitive control following the detection of conflict. The demonstration that the conflict monitoring system operates across distinct domains is critical to the conflict monitoring account of the bilingual advantage (Abutalebi et al., 2012; Costa et al., 2009), because language switching should only improve conflict monitoring in non-linguistic domains if conflict monitoring is domain-general. Put another way, practice-related improvements in a linguistic-specific conflict monitoring resource would not impact a separate, non-linguistic resource; thus, bilinguals should only exhibit improved conflict monitoring on non-linguistic tasks (i.e., the observed

bilingual advantage) if language switching engages the same, domain-general system that is employed on non-linguistic tasks. The conflict monitoring account of the bilingual advantage is only viable because conflict adaptation, and by extension, the conflict monitoring system, appears to be domain-general.

Since Experiment 1 supports the notion that domain-general conflict monitoring processes subserve conflict adaptation effects, conflict adaptation can be used as an indirect measure of conflict monitoring abilities. The conflict adaptation paradigm, in which performance is examined as a function of both preceding and current trial type, can be used to break-up conflict monitoring into its constituent components. Specifically, performance on CI trials assesses conflict detection abilities, because participants encounter an initial conflict in a sequence. On such trials, they must notice the competing representations in the input and recruit domain-general cognitive control resources to help override the irrelevant representation. On the other hand, performance on II trials reflects flexible adjustments in cognitive control, because participants encounter conflict after processing conflict on an immediately preceding trial. On these trials, the extent to which cognitive control is engaged following the detection of conflict on the preceding trial should influence performance; II performance will be better for individuals who reactively recruit cognitive control to a greater extent. Thus, the conflict adaptation paradigm can be used to delineate separable processes contributing to conflict monitoring.

As outlined above, recent research examining the bilingual advantage in cognitive control has attributed this advantage to improved conflict monitoring abilities (Abutalebi et al., 2012; Costa et al., 2009; Hilchey & Klein, 2011). If this is

indeed the source of the bilingual advantage, then bilinguals should perform differentially than monolinguals on the conflict adaptation paradigm, given that conflict adaptation indexes conflict monitoring abilities. Moreover, assuming that bilinguals indeed possess superior conflict monitoring skills, then the conflict adaptation paradigm can help determine whether bilinguals are particularly better at conflict detection, at reactively adjusting cognitive control recruitment, or both.

The purpose of Experiments 2 and 3 was to investigate the conflict monitoring account of the bilingual advantage by comparing conflict adaptation effects in bilinguals and monolinguals. Experiment 2 used the Stroop task to test conflict adaptation behaviorally in bilinguals and monolinguals, whereas Experiment 3 examined whether the neural signatures of conflict adaptation were different for bilinguals and monolinguals. More specifically, previous studies have indicated that, following conflict trials, monolinguals exhibit reduced activation in the ACC and increased activation in pre-frontal control regions in response to additional conflict (Botvinick et al., 1999; Kerns et al., 2004; Yeung, Botvinick, & Cohen, 2004). The present dissertation examines whether these same changes in activation also occurred in bilinguals, and if so, whether they occurred to a different extent.

# Chapter 3: Experiment 2

## *Overview*

Although conflict adaptation is one of the behavioral hallmarks of conflict monitoring, which is the theorized source of the bilingual advantage, no one has yet compared the magnitude of conflict adaptation in bilinguals and monolinguals. Experiment 2 was designed to examine behavioral conflict adaptation effects in balanced bilinguals and in monolinguals. If balanced bilinguals indeed have higher conflict monitoring abilities than monolinguals, they should exhibit superior conflict detection, greater moment-by-moment adjustments in cognitive control, or both. To investigate these predictions, I tested balanced Spanish-English bilinguals and English monolinguals on a single-task color-word Stroop containing the four conflict adaptation conditions, CC, CI, IC, and II. Performance on CI trials reflects conflict detection, because these trials require resolving conflict when the preceding trial did not contain conflict. Performance on II trials reflects reactive recruitment of cognitive control, because these trials involve resolving conflict after encountering conflict on the previous trial.

A secondary goal of Experiment 2 was to separate facilitation from interference effects in bilinguals and monolinguals. On traditional versions of Stroop-like tasks, the overall interference effect, calculated by the difference in performance on congruent and incongruent trials, captures both facilitation and interference processes (Kane & Engle, 2003). That is, congruent trials, for which the irrelevant

stimulus dimension matches the relevant stimulus attribute, actually improve (or facilitate) performance relative to neutral trials in which the irrelevant dimension is unrelated to the relevant attribute. On the other hand, incongruent trials, for which the irrelevant stimulus dimension mismatches the relevant dimension, impair (or interfere with) performance relative to neutral trials. Such neutral trials are distinct from congruent and incongruent trials in that their irrelevant stimulus dimension is completely unrelated to the relevant stimulus dimension. For instance, in Stroop, neutral trials would consist of non-color words printed in a variety of font colors (e.g., "horse" in green ink), whereas both congruent and incongruent trials consist of color words printed in a variety font colors (e.g., "green" or "blue" in green ink). The inclusion of neutral trials allows the traditional interference effect to be decomposed into two parts, facilitation and interference, by providing an intermediate performance reference point.

Separating interference and facilitation is important when examining individual differences in inhibitory control; indeed, previous research has found that, relative to low working memory capacity participants, individuals with high working memory capacity exhibit both decreased facilitation and decreased interference, apparently because they are better maintaining the task goal of suppressing the irrelevant stimulus dimension (Kane & Engle, 2003). Although some studies have claimed to demonstrate a bilingual advantage in inhibitory control (Bialystok et al., 2004), most of these have employed a conglomerate interference measure encompassing both facilitation and interference effects. Thus, instances showing less interference in bilinguals could be due to reduced interference, reduced facilitation, or

both. Similarly, for studies that find comparable overall interference effects in bilinguals and monolinguals (Costa et al., 2009; Martin-Rhee & Bialystok, 2008), it does not necessarily follow that bilinguals do not have reduced interference; bilinguals may have reduced interference but larger facilitation, or vice versa. Indeed, one study that used neutral trials to calculate facilitation and interference on a numerical Stroop task, in which participant had to name the number of elements in a sequence, which was either the same (e.g., 1, 22, 333) or different (e.g., 2, 33, 111) from the numerical value of the individual elements, found that bilinguals had increased facilitation but decreased interference relative to monolinguals (Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010). Crucially, this result might have been interpreted as comparable overall interference effects if neutral trials had not been included. Unfortunately, this result has been given relatively little attention in the literature, despite its importance for characterizing the bilingual advantage. Reduction in both facilitation and interference would indicate superior task maintenance, whereas reduction in interference alone may indicate better online conflict resolution. By using this finer-grained assessment of interference effects, we can better determine the locus of the bilingual advantage.

Finally, Experiment 2 examined whether the bilingual advantage in cognitive control applies to representational conflict, response conflict, or both. Representational conflict occurs when multiple mental tokens representing different concepts compete for selection. For example, in the Stroop task, incongruent stimuli, such as "blue" written in green ink, invoke two incompatible representations, the concept of 'blue' and the concept of 'green.' Response conflict, in contrast, occurs

when multiple motor outputs compete for selection. In our Stroop example, the button press for blue competes with the button press for green, creating response conflict. These conflict types have been shown to engage distinct neural regions (January et al., 2009; Milham et al., 2001, 2003), suggesting that they are separate abilities (although they will often co-occur). Logically, bilingualism induces both representational and response conflict. When naming an object, bilinguals activate (at least) two competing lexical representations, one from each language, and must select which word to produce (Kroll, Bobb, Misra, & Guo, 2008). However, most studies on the bilingual advantage have either confounded representational and response conflict (Abutalebi et al, 2012; Costa et al., 2009, Hernández et al., 2010) or have used tasks (e.g., the Simon task) that exclusively engage response conflict (Bialystok et al., 2004). Thus, it is unclear whether the advantage exists for both types of conflict resolution.

As discussed in Experiment 1, representational conflict can be isolated from response conflict by modifying the Stroop task to include two types of incongruent trials, 'response-eligible' and 'response-ineligible' (January et al., 2009; Milham et al., 2001, 2003). In response-eligible (RE) trials, the name of the color word is one of the possible button responses, inducing both representational conflict between the color word meaning and font color *and* response conflict between the button corresponding to the color word and the button corresponding to the font color. However, in response-ineligible (RI) trials, the color word name is not one of the response options, so only representational conflict is induced. Specifically, in a Stroop task with three response options, (e.g., blue, yellow, and green), the word

meaning on RE trials would always be "blue," "yellow," or "green," whereas the word meaning on RI trials would only be other colors, like "red," "orange," or "brown." Using such a design can tell us whether the bilingual advantage applies to representational conflict, response conflict, or both.

I expected to observe standard interference effects, where participants exhibit the highest accuracy and fastest response times on congruent trials, followed by neutral, RI-incongruent, and RE-incongruent trials, respectively. I hypothesized that bilinguals would be faster and more accurate than monolinguals across current trial types (congruent, neutral, RI-incongruent, and RE-incongruent) but that their overall interference effect (congruent versus RE-incongruent) would be comparable to that of monolinguals, replicating previous findings of a global bilingual advantage (Bialystok et al., 2004; Costa et al., 2009; Hilchey & Klein, 2011; Martin-Rhee & Bialystok, 2008). However, I hypothesized that bilinguals might experience greater facilitation (congruent versus neutral) and less interference (neutral versus RI-incongruent; neutral versus RE-incongruent) than monolinguals when comparing to the neutral baseline, replicating the findings of Hernández et al. (2010).

Regarding conflict adaptation effects, I predicted that, compared to monolinguals, bilinguals should exhibit superior conflict detection, superior reactive control, or both. Superior detection would be reflected in faster and more accurate performance on CI trials, whereas superior reactive control would be reflected in faster and more accurate performance on II trials.

*Method*

Participants

Participants included 33 balanced Spanish-English bilinguals (24 females; $M_{age}$ = 20.19, $SD_{age}$ = 1.94)[5] and 33 English monolinguals (27 females; $M_{age}$ = 19.88, $SD_{age}$ = 1.75) recruited from the University of Maryland, College Park community. Spanish-English bilinguals were recruited via flyers and e-mail advertisements. It was confirmed prior to scheduling that bilinguals were fluent in both Spanish and English and had had exposure to both languages prior to age 10. English monolinguals were recruited from a mass screening questionnaire administered through the Psychology department to match bilingual participants on age, gender, education, SES, and parental education. Language status of both groups was verified during the study via a language history questionnaire (see Appendix A). The questionnaire asked participants to indicate the amount of time spent speaking English versus Spanish on a 7-point scale (1: "Always English" – 7: "Always Spanish") at different times of their life (prior to starting school, during elementary school, during middle school, during high school, and during college/adulthood) and in different settings (at home, at school, with friends). It also asked participants to report their proficiency on a 4-point scale (1: "Not at all proficient" – 4: "Fluent") in speaking and listening for English, Spanish, and any other languages they might know. Bilinguals met the language criteria for inclusion if they indicated using both Spanish and English prior to entering middle school, if they self-rated their proficiency as at least a 3 ("fairly proficient") in both speaking and listening for both Spanish and English, if they

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[5] One bilingual participant did not report age.

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currently used both languages in their daily lives, and if they did not indicate

proficiency of 3 or higher in both speaking and listening in a third language.

Monolinguals met the language criteria for inclusion if their native language was

English, if they did not report exposure to a second language prior to starting school,

if they did not report a proficiency of 3 or higher in both speaking and listening in a

second language, and if they did not currently use a second language (outside of

formal school instruction). Depending on their preference, all participants received

either 1 extra credit towards coursework or $10 for their participation. If an

individual's overall accuracy on the task was less than 75%, that subject was dropped

from analyses and another subject from the same language group was recruited to

participate instead; no bilinguals met this criterion for exclusion, but this occurred for

one monolingual participant whose overall accuracy was 67%. Prior to data analyses,

an additional 14 subjects participated but were excluded because they did not meet

the language requirements for either group.

Materials and Procedure

The study included a color-word Stroop task and a background questionnaire.

The Stroop task was administered in two blocks, with a break in between them. Each

list contained 294 trials in total, 121-122 each of congruent and incongruent (counter-

balanced across the lists) and the remaining 51 were neutral to serve as a baseline.

Neutral words were matched to color-word stimuli on frequency and length.

Incongruent stimuli were divided equally between RE and RI trials to assess the

separate contributions of response conflict and representational conflict to

interference effects, with response-eligible words including blue, green, and yellow

and response-ineligible words including red, brown, and orange. All Stroop stimuli appeared in one of three colors, blue, yellow, or green, with 98 trials of each color. Trials were sequenced to include 48 of each conflict adaptation condition, CC, CI, IC, and II.

Participants were instructed to respond to the font color of the word via button push as quickly and accurately as possible. Each Stroop trial began with a fixation cross that appeared for 500ms in the center of the screen. The cross was then replaced by a Stroop stimulus, which remained on screen for 1000ms and was followed by a 1000ms blank screen.

After finishing the Stroop task, participants answered a language background and demographics questionnaire (see Appendix A) administered via the online survey host Qualtrics (http://www.qualtrics.com/). Monolinguals were not required to complete the final section of this survey, which asked about participants' English language skills, their frequency of L1 and L2 usage in daily life, their dominant or preferred language, and language-switching.

*Results*

Two separate analyses were conducted, one to examine the effect of bilingualism on interference effects and the other to examine the effect of bilingualism on conflict adaptation effects. Both reaction time analyses adjusted for the effect of outliers by computing the mean reaction time of all correct trials for each subject and replacing trials more than 2.5 standard deviations beyond each subject's mean with the 2.5 standard deviation threshold value.

Interference Results

To examine the effect of current trial type on accuracy, I conducted a 2 x 4 ANOVA with language group (bilingual versus monolingual) as a between-subjects factor and trial type (congruent, neutral, RI-incongruent, and RE-incongruent) as a within-subjects factor. This revealed a significant main effect of current trial type ($F(3, 192) = 38.34$, $p < .0001$), but no effect of language group and no language group x trial type interaction ($p$s $> .31$). Planned comparisons of congruent versus neutral, neutral versus RI-incongruent, and RI-incongruent versus RE-incongruent were conducted using one-tailed paired-sample $t$-tests to probe the expected congruency effects. One-tailed t-tests were used because the hypothesized effect of congruency is directional and well-supported by previous literature (January et al., 2009; Milham, Banich, & Barad, 2003; Milham et al., 2001). As seen in Figure 1, participants were significantly more accurate on congruent trials than on neutral trials ($t(65) = 1.64$, $p = .05$; BF $= 0.45$), they were equivalently accurate on neutral and RI-incongruent trials ($t(65) = 0.90$, $p = .38$; BF $= 0.18$), and they were significantly more accurate on RI-incongruent than on RE-incongruent trials (t(65) = 7.49, p $< .0001$; BF $> 1,000$). However, note that for the congruent versus neutral comparison, the BF value indicates support for the null hypothesis of no difference between the conditions, suggesting that there was no facilitation effect in accuracy.
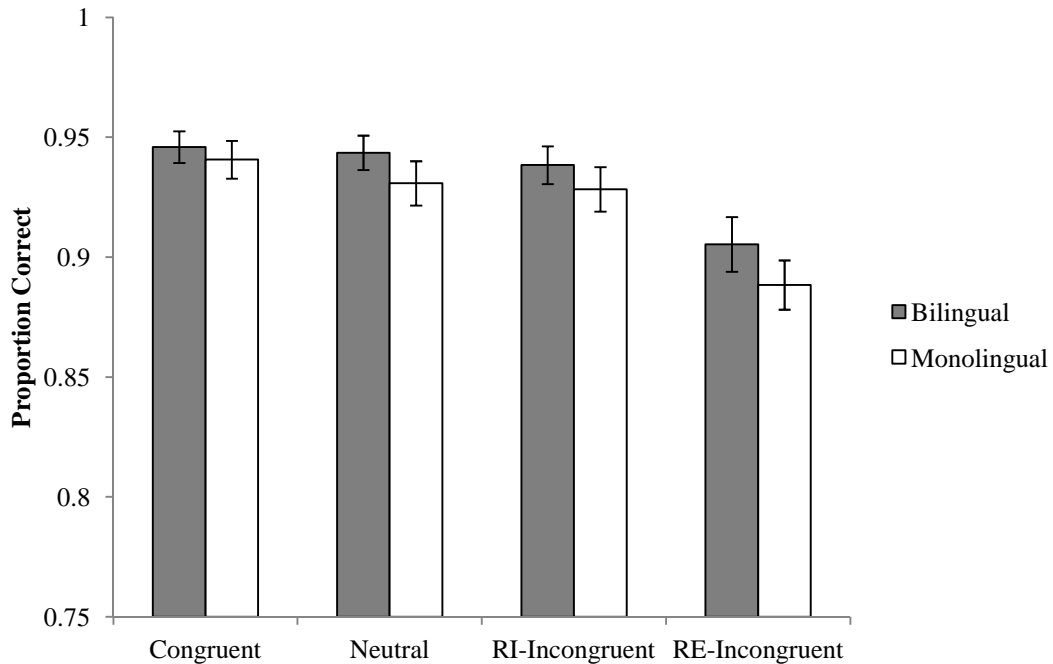
*Figure 1. Proportion correct by current trial type and language group.*

For reaction times, a 2 x 4 mixed-ANOVA with language group (bilingual versus monolingual) as a between-subjects factor and trial type (congruent, neutral, RI-incongruent, and RE-incongruent) as a within-subjects factor revealed a significant main effect of language group ($F(1, 64) = 7.39$, $p = .008$), indicating that monolinguals responded significantly faster than bilinguals (see Figure 2). There was also a significant main effect of trial type ($F(3, 192) = 87.80$, $p < .0001$). However, the interaction was not significant, indicating that monolinguals were faster than bilinguals across trial types ($F(3, 192) = 1.49$, $p = .22$).
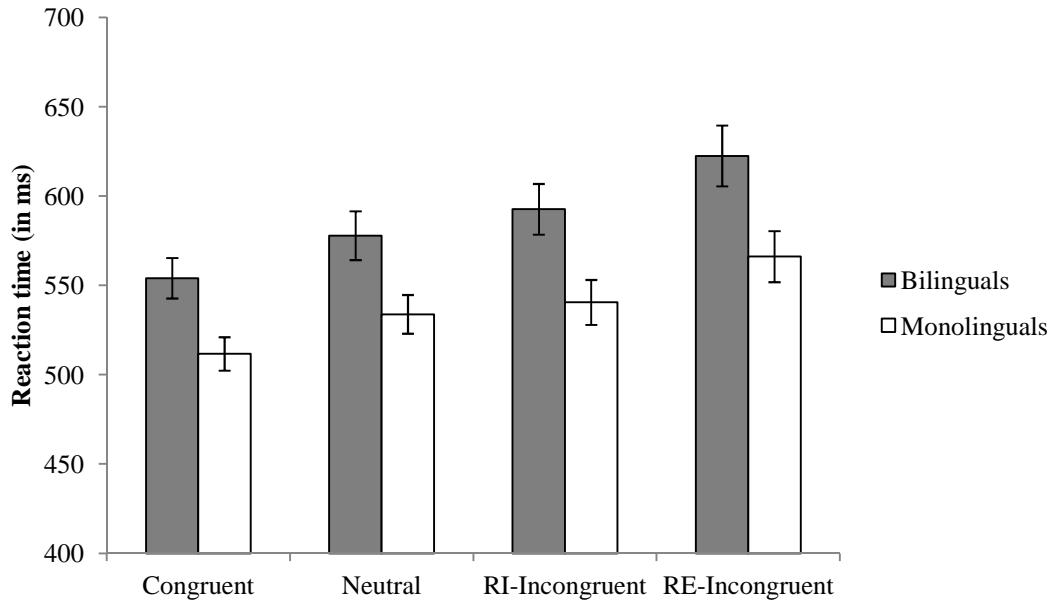
*Figure 2. Reaction time by current trial type and language group.*

To investigate the hypothesized congruency effects, I conducted planned comparisons of congruent versus neutral, neutral versus RI-incongruent, and RI-incongruent versus RE-incongruent trials, using one-tailed paired-sample $t$-tests. As expected, participants were significantly faster on congruent trials than on neutral trials ($t(65) = -8.29$, $p < .0001$; BF > 1,000), significantly faster on neutral than RI-incongruent trials ($t(65) = -3.70$, $p < .0001$; BF = 60.42), and significantly faster on RI-incongruent than RE-incongruent trials ($t(65) = -8.02$, $p < .0001$; BF > 1,000; see Figure 2).

Conflict Adaptation Results

To examine conflict adaptation effects, I conducted a 2 (preceding trial type) x 2 (current trial type) x 2 (language group) mixed-ANOVAs separately for accuracy and reaction time (RT) on conflict adaptation trials only (i.e., CC, CI, IC, and II). Preceding trial type and current trial type were within-subjects factors, and language

group was a between-subjects factor. All post-error trials were excluded from analyses, because error monitoring may reflect a dissociable process from conflict monitoring (Ullsperger & von Cramon, 2001). Trials involving response repetitions and/or negative priming were also excluded because they can lead to sequential performance modulations that are unrelated to conflict. Specifically, response repetitions, when the correct response is the same as the response on the preceding trial, typically lead to better performance and can be confounded with conflict adaptation conditions (Mayr et al., 2003; Nieuwenhuis et al., 2006). In contrast, negative priming, which occurs when the word on the preceding trial is the same as the color on the current trial, is associated with poorer performance because if participants suppressed the word meaning on the preceding trial and that same meaning is associated with the correct response on the current trial, then it may need to be reactivated before the participant can respond (Kane, May, Hasher, Rahhal, & Stoltzfus, 1997; May, Kane, & Hasher, 1995; Neill, 1977).

Accuracy analyses revealed a significant main effect of preceding trial type ($F(1, 64) = 9.29$, $p = .003$), a significant main effect of current trial type ($F(1, 64) = 35.25$, $p < .0001$), and a significant preceding trial and language group interaction ($F(1, 64) = 4.78$, $p = .03$). The three-way interaction between preceding trial type, current trial type, and language group was not significant ($F(1, 64) = .165$, $p = .69$). No other effects were significant ($p$s > .21).

*Figure 3. Proportion correct by language group and conflict adaptation condition.*CC: preceding congruent, current congruent. CI: preceding congruent, current incongruent. IC: preceding incongruent, current congruent. II: preceding incongruent, current incongruent.

As can be seen in Figure 3, the main effect of preceding trial type emerged because participants were significantly more accurate after incongruent trials than they were after congruent trials. The current trial type effect reflected the traditional interference effect, namely that participants were less accurate on incongruent trials than on congruent trials. To probe the interaction between preceding trial and language group, I conducted post-hoc pair-wise comparisons with a Bonferroni corrected alpha-threshold of .0125. Independent-samples $t$-tests found that bilinguals did not significantly differ from monolinguals in accuracy when the preceding trial was congruent ($t(64) = 1.32$, $p = .19$; BF = 0.54) or incongruent ($t(64) = 0.05$, $p = .96$; BF = 0.24). However, paired-samples t-tests revealed that whereas monolinguals exhibited significantly lower accuracy ($t(32) = -3.71$, $p < .001$; BF = 51.03) following congruent than incongruent trials, bilinguals exhibited equivalent accuracy ($t(32) = -0.25$, $p = .80$; BF = 0.18) following congruent and incongruent trials (see Table 2).

Visual inspection of Figure 3 suggests that the lower accuracy in monolinguals following congruent trials is primarily driven by relatively poorer performance on CI trials.

Table 2

*Proportion Correct (and Standard Error) by Preceding Trial and Language Group*

| Language group | Preceding Trial Type | |
|---|---|---|
| | Congruent | Incongruent |
| Bilinguals | .93 (.01) | .93 (.01) |
| Monolinguals | .91 (.01) | .93 (.01) |

For reaction time analyses, there was a significant main effect of language group ($F(1, 64) = 8.99$, $p = .004$) and a significant main effect of current trial type ($F(1, 64) = 180.94$, $p < .0001$). As can be seen in Figure 4, the main effect of language group indicated that monolinguals were significantly faster than bilinguals. The effect of current trial type replicated standard interference effects, with significantly slower performance on incongruent than on congruent trials.

There was also a marginal (i.e., $p < .1$) main effect of preceding trial type ($F(1, 64) = 3.19$, $p = .08$), which indicated that participants were faster following incongruent than congruent trials. Finally, a marginal current trial by language group interaction emerged ($F(1, 64) = 3.52$, $p = .07$). However, these effects should not be over-interpreted, since they did not reach significance. No other effects reached significance ($p$s $> .16$).
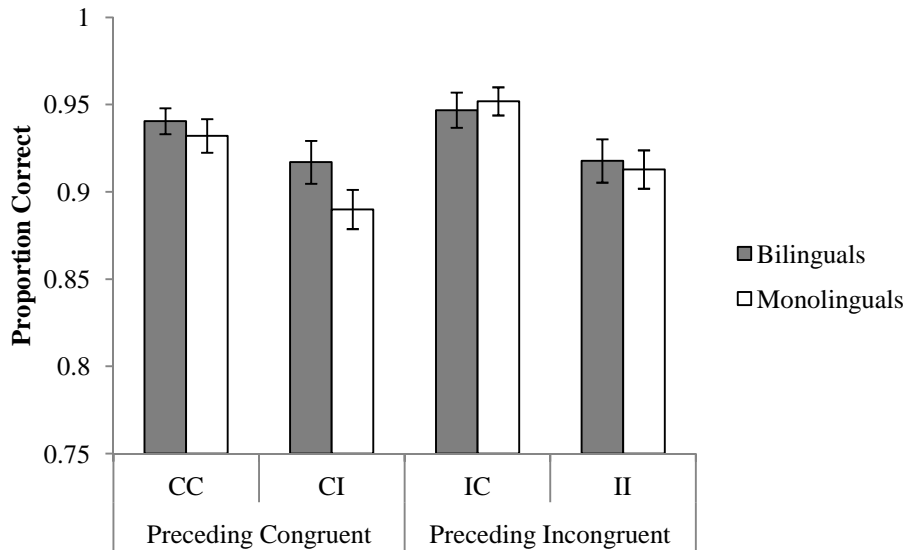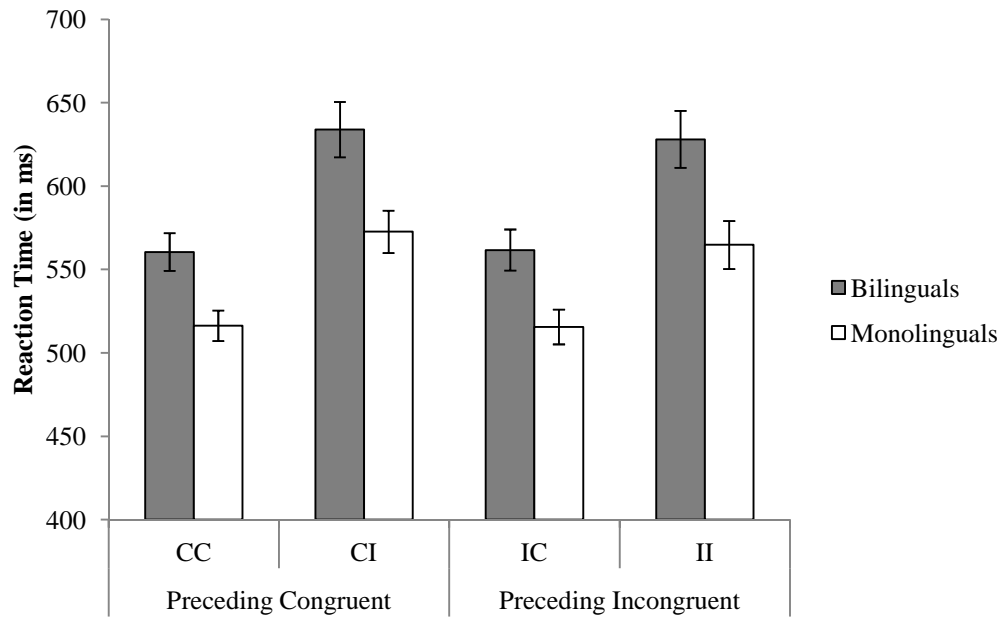
*Figure 4. Reaction time by language group and conflict adaptation condition.* CC: preceding congruent, current congruent. CI: preceding congruent, current incongruent. IC: preceding incongruent, current congruent. II: preceding incongruent, current incongruent.

To investigate the current trial by language group interaction, I computed interference effects (I-C) for each subject and conducted an independent-samples t-test comparing bilinguals and monolinguals. This revealed that the interference effect was marginally larger in bilinguals than in monolinguals ($t(64) = 1.93$, $p = .06$; BF = 1.35; see Table 3). Note, however, that the BF value indicates only weak support for a larger interference effect in bilinguals than monolinguals.

Table 3

*Mean RTs (and Standard Errors) for the Interference Effect by Language Group*

| Language group | Interference effect |
|---|---|
| Bilinguals | 70.25 (7.19) |
| Monolinguals | 52.95 (5.36) |

*Discussion*

The findings from Experiment 2 provided mixed support for the existence of a bilingual advantage in conflict monitoring. With regards to reaction time, bilinguals actually exhibited a disadvantage compared to monolinguals, responding more slowly across trial types. However, in accuracy, an interaction between language group and preceding trial type revealed that monolinguals had decrements in accuracy following congruent trials compared to incongruent trials, whereas bilinguals showed no such decline. The implications of these effects are discussed below.

Interference Effects

The analysis of current trial type showed that while bilinguals and monolinguals were equivalently accurate across congruent, neutral, RI-incongruent and RE-incongruent trials, monolinguals were faster than bilinguals regardless of trial type. This result was surprising, because it contradicted previous evidence that bilinguals are faster than monolinguals on cognitive control tasks (Bialystok, 2010; Bialystok et al., 2004; Costa et al., 2009; Hernández et al., 2010; Martin-Rhee & Bialystok, 2008). It is, however, worth noting that bilinguals were at least numerically more accurate than monolinguals across trial types, suggesting that the apparent bilingual disadvantage in reaction time may actually reflect a speed-accuracy trade-off, wherein monolinguals are responding more quickly at the expense of accuracy. Still, the present results call into question the robustness and consistency of the bilingual advantage.

These are not the first results that have failed to find a bilingual advantage in cognitive control. Paap and Greenberg (2013) recently tested a heterogeneous sample

of bilinguals and English-speaking monolinguals on a diverse set of executive function tasks, including Simon, Flanker, Color-Shape Shifting, Antisaccade, and Raven's Progressive Matrices, and failed to find a significant bilingual advantage on any measure, even when controlling for parental education and even after comparing a subset of the most proficient bilinguals to a subset of monolinguals with the least second-language experience. One thing that the present study and the Paap and Greenberg study have in common is that they were both conducted in "monolingual" environments (e.g., the United States), where there is a single, predominant language; in contrast, many studies that have found evidence for a bilingual advantage (Costa, Hernández, & Sebastián-Gallés, 2008; Costa et al., 2009; Hernández et al., 2010) have been conducted in "bilingual" environments (e.g., Barcelona), where there are two prevalent languages. This raises the interesting question of whether particular types of bilingual language experience might influence cognitive control differently.

In particular, bilinguals in environments where two languages are spoken frequently may have more practice flexibly switching between their two languages. Given the evidence reviewed in Chapter 1 that language-switching engages neural resources associated with conflict monitoring (Abutalebi et al., 2012; Gold et al., 2013), it is possible that increased experience with language-switching drives performance boosts in conflict monitoring. If this is the case, then larger advantages are to be expected in bilingual populations that live in "bilingual" environments than those living in "monolingual" environments. However, before entirely embracing the notion that only certain types of bilingualism are beneficial to conflict monitoring abilities, recall that the present study also found that the effect of language group on

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Stroop accuracy was modulated by preceding trial type, providing the first evidence of different sequential conflict effects in bilinguals and monolinguals.

Conflict Adaptation Effects

Despite failing to find a global bilingual advantage in accuracy or reaction time, Experiment 2 did provide evidence that earlier encounters with conflict may influence bilinguals and monolinguals differentially. Specifically, whereas bilinguals were equally accurate following congruent and incongruent trials, monolinguals exhibited lower accuracy after congruent trials. This effect appeared to be driven by poorer performance on CI trials, where individuals must detect initial conflicts between the font color and word meaning in order to respond correctly. One interpretation of this finding is that monolinguals may deactivate cognitive control resources or fail to maintain the task goal following congruent trials, where the prepotent response (e.g., reading the word) would enable correct responding; then, after encountering conflict, they would reactively recruit cognitive control, allowing better accuracy on II trials. Conversely, bilinguals seem to be ready to resolve conflict regardless of whether the preceding trial type is congruent or incongruent. This result is consistent with the conflict monitoring account of the bilingual advantage (Costa et al., 2009; Hilchey & Klein, 2011), because it suggests that bilinguals are better than monolinguals at detecting conflict.

This interpretation is complicated, however, by the finding that bilinguals were slower overall and had marginally larger interference effects in RT than monolinguals did. Although bilingualism seemed to benefit accuracy during conflict detection, it also seemed to generally slow processing. Why might bilingualism

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induce slower but more accurate responding? One possibility is that, because bilinguals encounter linguistic competition more frequently than monolinguals, errors in conflict resolution are more costly. Monolinguals may be able to resolve competition relatively quickly and still make very few errors in comprehension or production. However, if bilinguals sped up to achieve the same error *rate* as monolinguals, this could drastically increase the *number* of errors that they make, considering that they are constantly facing competition between their language systems. Thus, bilinguals' apparent speed-accuracy trade-off could reflect a strategy to reduce the number of cross-linguistic errors they experience.

Conclusions

Although the evidence for the bilingual advantage in conflict monitoring in Experiment 2 was mixed, the results open the door to further investigations of trial-by-trial adjustments in cognitive control in bilinguals and monolinguals. Since Experiment 2 found that monolinguals' accuracy was adversely affected when the preceding trial was congruent, it would be interesting to assess changes in the neural conflict monitoring system that protect bilinguals from this performance decrement. The purpose of Experiment 3 was to further examine the effect of bilingualism on sequential modulations in cognitive control by examining the neural systems underlying conflict adaptation in bilinguals and monolinguals.

# Chapter 4: Experiment 3

*Overview*

The conflict monitoring theory originally developed from observations regarding ACC activity in response to conflict. Using a Flanker task in which a target center arrow pointed in the same direction (compatible) or the opposite direction (incompatible) as distracting flanker arrows, Botvinick and colleagues (1999) noted that activity in the ACC increased in response to incompatible trials, but that this activation was reduced if the previous trial was also incompatible – in other words, ACC activity demonstrated conflict adaptation! The authors proposed that the ACC reacted when conflict was highest (e.g., on CI trials), triggering adjustments in cognitive control to reduce subsequent conflicts. Moreover, the increase in ACC activity for CI relative to II was positively correlated with the increase in reaction time for CI relative to II, suggesting that ACC activity indexes the extent of behavioral conflict adaptation. Subsequent studies revealed that the ACC is not the only brain region whose activity corresponds with the conflict adaptation effect, but that the dorsolateral prefrontal cortex (dlPFC) is more active following conflict trials and associated increases in ACC activity, providing evidence that ACC is indeed signaling to pre-frontal regions to enact greater control (Kerns et al., 2004).

Thus, the neural correlates of conflict adaptation are well-documented in monolinguals, providing us with candidate regions, namely the ACC and dlPFC, to investigate as possible sources of the bilingual advantage in conflict monitoring. Few

studies, however, have examined the underlying neural network supporting the bilingual advantage. One compelling exception is a recent study by Abutalebi et al. (2012), which demonstrated that language-switching and conflict in the non-verbal Flanker task co-activates the ACC. Since the ACC is the structure thought to be responsible for detecting conflict and signaling adjustments in control in monolinguals (Botvinick et al., 2001, 2004), this suggests that bilinguals recruit the same conflict monitoring network for resolving non-linguistic conflict and for switching between their languages. Additionally, relative to monolinguals, bilinguals had reduced ACC activity in response to conflict, despite experiencing less interference behaviorally (Abutalebi et al., 2012). Language-switching has also been found to recruit the dlPFC, which is implicated in general conflict resolution (Hernandez, 2009; Hernandez, Martinez, & Kohnert, 2000), and the left caudate (Abutalebi, Brambati, Annoni, Moro, Cappa, & Perani, 2007; Abutalebi, Della Rosa, Ding, Weekes, Costa, & Green, 2013; Crinion et al., 2006). Activation of left caudate is typically observed during control of motor output and is reduced in disorders that impair motor control, like Huntington's and ADHD (Gavazzi et al., 2007; Rubia, Overmeyer, Taylor, Brammer, Williams, Simmons, & Bullmore, 1999; Shadmehr & Holcomb, 1999). These findings confirm that language-switching invokes similar neural resources as general conflict processing, making language-switching a plausible mechanism for improving cognitive control abilities in bilinguals.

Additional evidence for the role of these control regions in the bilingual advantage comes from differences in task-switching performance between older adult bilinguals and age-matched monolinguals. Relative to monolinguals, bilinguals

demonstrated reduced switch-costs in a color-shape decision task where participants alternated between identifying the color and identifying the shape of a picture (Gold et al., 2013). This performance boost was accompanied by reduced activation of the ACC, the left dlPFC, and the left vlPFC (Gold et al., 2013). That bilinguals exhibit better switching performance while simultaneously engaging to a lesser extent neural resources involved in conflict detection (ACC) and resolution (left dlPFC and vlPFC) suggests that their conflict monitoring system is more efficient as a result of extensive practice with language-switching.

Taken together, findings from bilingual language- and task-switching studies support the conflict monitoring account of the bilingual advantage, because switching engages the same regions that exhibit real-time modulations in neural activity during conflict monitoring. The original conflict monitoring theory (Botvinick et al., 1999, 2001) predicts behavioral and neural 'conflict adaptation' effects: individuals are better (i.e., faster and more accurate) at resolving a current conflict if it occurs immediately after another conflict than if it was not preceded by conflict (Botvinick et al., 1999, 2001; Gratton, Coles, & Donchin, 1992; Ullsperger, Bylsma, & Botvinick, 2005); additionally, when participants encounter randomly alternating conflict and non-conflict trials, ACC activity is enhanced for initial conflict trials relative to subsequent conflict trials, mimicking behavioral conflict adaptation (Botvinick et al., 1999; Botvinick, Cohen, & Carter, 2004). Interestingly, the ACC may serve to detect initial conflicts and signal adjustments in prefrontal control regions. This notion is supported by the finding that ACC activation in response to initial conflicts positively correlates with faster and more accurate performance when

resolving conflicts one trial later, as well as with prefrontal cognitive control activation, particularly in the dlPFC (Kerns et al., 2004). Ultimately, evidence from conflict adaptation paradigms suggests that the ACC and prefrontal control regions compose a neural conflict monitoring network wherein the ACC detects conflicts and helps initiate engagement of cognitive control, thus improving subsequent conflict resolution performance (Kerns et al., 2004). Given the theory that bilinguals possess better conflict monitoring abilities, it is important to investigate the neural system underlying conflict monitoring in bilinguals.

Despite evidence that the bilingual advantage may stem from improved conflict monitoring abilities, no study to date has compared conflict adaptation effects in bilinguals and monolinguals, so it is unknown whether bilinguals and monolinguals exhibit differential real-time modulations in cognitive control. The Abutalebi et al. (2012) study used traditional interference effects, comparing congruent and incongruent trials, rather than conflict adaptation effects to investigate the conflict monitoring system. Because the ACC and associated prefrontal control regions respond differently depending on the preceding trial type (Botvinick et al., 1999, 2001; Kerns et al., 2004), it makes sense to examine the role of both preceding and current trial types in activating the bilingual conflict monitoring network. If the bilingual advantage reflects better conflict monitoring, then bilinguals should exhibit differential patterns of activation in the neural conflict monitoring network when initially detecting conflict, relative to trials where conflict detection is not necessary. Changes in activation should correspond to better performance either in detecting conflict or in reactively adjusting cognitive control recruitment.

The goal of Experiment 3 was to investigate the neural underpinnings of conflict monitoring in bilinguals compared to monolinguals by using a conflict adaptation paradigm. As discussed in earlier chapters, this paradigm can be used to break-up conflict monitoring into its constituent components because performance is examined as a function of both preceding and current trial type. Conflict detection is indexed by performance on CI trials, where participants encounter conflict that was not immediately preceded by conflict. On such trials, they must detect the new presence of incompatible representations and activate domain-general cognitive control resources to help override the irrelevant one. In contrast, on II trials, participants have already had to detect conflict and engage cognitive control on the preceding trial. Thus, II trials index reactive adjustments in cognitive control, as II performance should be better among individuals who flexibly increase recruitment of cognitive control to a greater extent. In this manner, the processes underlying conflict monitoring can be isolated and examined using the conflict adaptation paradigm.

I tested early Spanish-English bilinguals and English monolinguals on a color-word Stroop containing the four conflict adaptation conditions, CC, CI, IC, and II. Under the conflict monitoring theory, I hypothesized that bilinguals should exhibit better performance than monolinguals on CI trials, reflecting superior conflict detection on new instances of incongruity, II trials, reflecting increased flexibility in adjusting cognitive control, or both. Moreover, I predicted that bilinguals would exhibit functional-anatomical differences compared to monolinguals in the neural conflict monitoring system associated with their heightened readiness for detecting conflict and engaging control. In monolinguals, detection of conflict is associated

with increased ACC activity, while resolution between competing representations involves the vlPFC and dlPFC (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Botvnick et al., 1999, 2001, 2004; Braver, Reynolds, & Donaldson, 2003; January et al., 2009; Kerns et al., 2004; Koechlin, Ody, & Kouneiher, 2003; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). I hypothesize that, in response to CI and II trials, bilinguals and monolinguals will exhibit differential activity in the ACC, vlPFC, and/or dlPFC, reflecting bilinguals' increased practice with conflict monitoring. On these trials, bilinguals may also recruit regions particularly implicated in language-switching, namely, the left caudate (Abutalebi et al., 2007, 2013; Crinion et al., 2006), to a greater extent than monolinguals, reflecting increased reliance on the switching mechanisms bilinguals use for routine language use.

### *Method*

Participants

Early Spanish-English bilinguals (n = 14; 7 female) and native English monolinguals (n = 14; 8 female) were recruited from the University of Maryland, College Park community via flyers, e-mail advertisements, and the Maryland Neuroimaging Center's website. All participants were right-handed, healthy young adults between the ages of 18 and 35. Exclusionary criteria included major hearing loss, uncorrected vision impairment, color-blindness, known psychological or neurological conditions, psychoactive medication, non-removable ferromagnetic bodily objects, and (in females) pregnancy. Individuals were also excluded if they did

not meet the language criteria for either group: Spanish-English bilingual participants were fluent in both Spanish and English, had had exposure to both languages prior to age 10, and were not proficient in a third language; English monolinguals were native American-English speakers who did not speak another language proficiently, had no more than minimal exposure to another language prior to age 10, and had never been immersed in a non-English speaking environment for an extended period of time. Two additional monolinguals participated but were excluded from analyses because they exhibited overall accuracy less than 75% (n = 1) or were undergoing working memory training through another study (n = 1). Participants were offered either 1 course extra credit per hour or $10 per hour for their participation.

Materials

During the fMRI scan, participants completed a color-word Stroop task (Stroop, 1935) containing six lists of 64 trials each. Of these, 28 were congruent trials where the word meaning and font color were the same, 28 were incongruent where the word meaning and font color were different colors, and 8 were neutral trials where the word meaning was unrelated to color. Stimuli were presented in blue, yellow, green, or red font colors, which corresponded to response buttons held underneath the left middle, left index, right index and right middle fingers, respectively. The font colors were equally distributed across the conditions to prevent bias towards a particular response. The word meaning on incongruent trials was always one of the possible response options (blue, yellow, green, or red), and neutral words were matched to the color words for frequency and length. Neutral trials were

not of primary interest, but were included to reduce predictability of the upcoming trial.

Because conflict adaptation is assessed by both the preceding (congruent or incongruent) and current trial type (congruent or incongruent), each run was sequenced to contain 12 of each of the four primary conditions of interest: preceding congruent and current congruent trials (CC), preceding congruent and current incongruent trials (CI), preceding incongruent and current congruent trials (IC), and preceding incongruent and current incongruent trials (II). Thus, across all six lists, there were 72 CC, 72 CI, 72 IC, and 72 II trials. The stimulus color was never repeated on adjacent trials, thus eliminating repetition priming. The sequence of trials was also restricted: the stimulus word on the preceding trial was never the font color on the subsequent trial. This was done to avoid negative priming effects, where individuals are slower to respond when the previously distracting information becomes the correct response on the next trial, perhaps because they must reactivate the previously suppressed information (Kane, May, Hasher, Rahhal, & Stoltzfus, 1997; May, Kane, & Hasher, 1995; Neill, 1977). Stimuli were presented at three different inter-stimulus intervals (ISIs), 3000, 4000, and 5000 ms, to estimate overlap between the blood-oxygen-level-dependent (BOLD) responses associated with adjacent stimulus events (Dale & Buckner, 1997). The ISIs were evenly distributed across the conflict adaptation conditions, so that there were 24 of each conflict adaptation/ISI combination (4 per run).

Participants also completed the language background and demographic questionnaire used in Experiment 2 to obtain information about socio-economic status, education, language proficiency, and typical language use (see Appendix A).

Procedure

Prior to the scan, participants provided informed consent and were given verbal instructions regarding the procedure of the Stroop task. Instructions informed them that they would see a series of color words presented one at a time and that they should indicate the font color of each word as quickly and accurately as possible, using the response buttons provided. They were told that they would first complete a practice task with an answer key, during which time they needed to learn which color corresponded to which button, since the answer key would not be provided after the practice. Then, they would proceed to six runs of about six minutes each of the actual task. Finally, they were informed of the importance of staying still for the duration of the scan.

Participants were fully screened to ensure they could safely enter the magnet room in accordance with University of Maryland IRB procedures. Following screening, participants were situated in the 3T Siemens scanner by an MR tech and an experimenter, who verified that participants were comfortable and could view the entire screen on which the task would be presented. Participants were given the four response buttons, two in each hand, and directed to keep their left middle, left index, right index, and right middle fingers over each button.

At the start of a localizer scan, participants were instructed to lie as still as possible for the remainder of their time inside the scanner. After the localizer,

participants completed 40 practice trials of Stroop while the high-resolution structural images were collected. During the practice, an answer key with the four response options and their corresponding colors was provided at the bottom of the screen. The experimenter monitored accuracy during practice to verify that participants learned the correct responses. Participants completed the practice at their own pace and were instructed to lie still and wait for the experimenter after they had finished.

After a brief four-volume echo-planar imaging scan and a gre-field mapping, the six task runs were administered in one of two orders, which were counterbalanced across participants—half the bilinguals and half the monolinguals received each order. Participants were asked if they had any questions about the task before they began. Written instructions were provided at the start of each run to remind participants of the response mappings and to respond as quickly and accurately as possible. Participant motion was monitored during each run, and they were reminded to keep still following any runs in which they exhibited sudden movements larger than 1 mm. Following these six runs, diffusion-tensor imaging data were collected.

After the scan, participants moved to another room to complete the background questionnaire, which was administered online via the Qualtrics survey host website.

Image Acquisition

Imaging was conducted on a 3T Siemens scanner with a 32-channel head coil at the Maryland Neuroimaging Center at University of Maryland. Prior to the functional scans, a high-resolution structural image was obtained for each subject (MPRAGE, 192 slice T1-weighted image, TR = 1900 ms, TE = 2.32 ms, flip angle =

9˚, FOV = 230 mm$^2$, matrix size = 256×256, TA = 4.43 min, resolution = 0.9×0.9×0.9 mm). Functional imaging data were collected using an event-related technique over 6 runs within a single session. For each run, 175 whole-volume scans were acquired over 5.93 minutes using an echo-planar imaging (EPI) sequence (36 interleaved transversal slices, TR = 2000 ms, TE = 24 ms, flip angle = 70˚, FOV = 192 mm$^2$, matrix size = 64×64, slice thickness = 3.2 mm, voxel size = 3.0×3.0×3.2 mm). Within each run, the EPI scans began 12 seconds before the appearance of the first trial.

Image Processing

All data were processed and analyzed using SPM8 (Statistical Parametric Mapping; http://www.fil.ion.ucl.ac.uk/spm) running on Matlab 7.7.0. Functional volumes were realigned to correct for head motion by first co-registering the first scan from each run to the first scan of the first run and then by realigning the images to the mean functional image. The realigned images were then slice-time corrected using sinc interpolation with the middle slice (slice 18) as the reference. After co-registering each subject's anatomical image to the mean functional image, the anatomical image was segmented by tissue type to determine parameters for spatial normalization. Using these parameters, the realigned, slice-time corrected functional images were normalized via trilinear interpolation to fit the MNI (Montreal Neurological Institute) template. Finally, images were smoothed using an 8 mm full-width at half-maximum (FWHM) Gaussian kernel.

Statistical analyses were computed at the subject-level using a general linear model with 10 predictors: filler (the first trial of each run), CC, CI, CN, IC, II, IN, NC, NI, and incorrect trials. Thus, nine predictors corresponded to the possible trial

types, as determined by both preceding and current trial congruency, and included only correct trials, and the tenth predictor included all incorrect trials. Responses were modeled as the convolution between a series of impulse (delta) functions representing each stimulus onset and the canonical hemodynamic response function. The contrast images from each subject were used as input to group-level analyses.

*Results*

Accuracy

Accuracy data were submitted to a 2 x 2 x 2 mixed-ANOVA with language group (bilingual, monolingual) as a between-subjects variable and preceding (congruent, incongruent) and current (congruent, incongruent) trial types as within-subjects variables. This revealed a significant main effect of preceding trial type ($F(1, 26) = 17.45$, $p < .001$), indicating that participants were less accurate following congruent trials ($M = .92$, $SE = .01$) than following incongruent trials ($M = .94$, $SE = .01$). A significant main effect of current trial type ($F(1, 26) = 10.94$, $p < .01$) demonstrated that participants were less accurate on incongruent trials ($M = .92$, $SE = .01$) than on congruent trials ($M = .95$, $SE = .01$), replicating the standard conflict effect. Finally, there was also a marginal preceding trial by language group interaction ($F(1, 26) = 3.85$, $p = .06$). No other main effects or interactions approached significance ($ps > .39$).

To explore the preceding trial by language group interaction, I conducted post-hoc pair-wise comparisons with a Bonferroni corrected alpha-threshold of .0125. Independent-samples t-tests found that bilinguals did not significantly differ from

monolinguals in accuracy when the preceding trial was congruent ($t(26) = 1.14$, $p = .27$; BF = 0.63) or incongruent ($t(26) = 0.34$, $p = .74$; BF = 0.37). However, paired-samples t-tests revealed that whereas monolinguals exhibited significantly lower accuracy ($t(13) = -3.21$, $p < .01$; BF = 10.71) following congruent than incongruent trials, bilinguals exhibited equivalent accuracy ($t(13) = -1.32$, $p = .21$; BF = 0.59) following congruent and incongruent trials (see Table 4).

Table 4

*Mean Proportion Correct (and Standard Error) by Language Group and Preceding Trial Type*

| Language group | Preceding Trial Type | |
| --- | --- | --- |
| | Congruent | Incongruent |
| Bilingual | .94 (.01) | .94 (.01) |
| Monolingual | .91 (.02) | .94 (.01) |

Thus, preceding trial type affected accuracy in monolinguals but not in bilinguals. An inspection of Figure 5 suggests that this effect is primarily driven by monolinguals' relatively poor performance on CI trials. Indeed, both language groups exhibited accuracy rates higher than 92% on all trial types, except that monolinguals responded correctly for only 89% of CI trials. This result suggests that monolinguals have difficulty resolving conflict on initial conflict trials when they have the added demand of detecting the presence of conflict. In contrast, bilingual accuracy does not appear to be hindered by conflict detection.
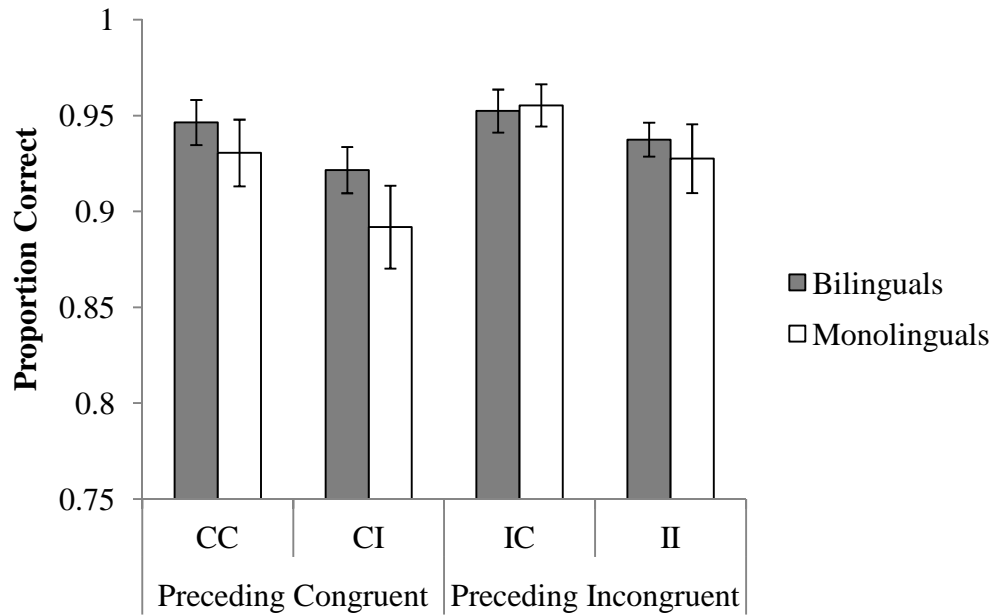
*Figure 5. Proportion correct for bilinguals and monolinguals by conflict adaptation condition.* CC: preceding congruent, current congruent. CI: preceding congruent, current incongruent. IC: preceding incongruent, current congruent. II: preceding incongruent, current incongruent.

Reaction Time

Reaction time (RT) analyses were conducted on correct trials only, since incorrect trials may involve separate underlying processes. To reduce the influence of outliers, I reset the value of RTs for trials that were more than 2.5 standard deviations beyond each subject's mean RT to the 2.5 standard deviation threshold value. A 2 x 2 x 2 mixed ANOVA with language group as a between-subjects factor and preceding and current trial types as within-subjects factors revealed a significant main effect of current trial type ($F(1, 26) = 64.16$, $p < .001$) on RT. No other main effects or interactions were significant ($p$s $> .11$). See Table 5 for a report of the mean and standard error of RTs in each condition.

Table 5

*Mean RT (and Standard Error) by Language Group and Conflict Adaptation Condition*

| Language group | Preceding Congruent | | Preceding Incongruent | |
|---|---|---|---|---|
| | CC | CI | IC | II |
| Bilinguals | 696.41 (32.78) | 788.02 (43.66) | 710.37 (40.60) | 785.26 (44.62) |
| Monolinguals | 632.72 (24.62) | 696.66 (27.78) | 637.04 (29.38) | 696.05 (31.70) |

*Note.* CC: preceding congruent, current congruent. CI: preceding congruent, current incongruent. IC: preceding incongruent, current congruent. II: preceding incongruent, current incongruent.

Thus, subjects were slower at responding on incongruent trials ($M = 746.26$, $SE = 26.68$) than on congruent trials ($M = 670.77$, $SE = 23.10$), replicating the classic Stroop conflict effect. However, I did not observe any significant RT differences between the language groups.

fMRI Results

To investigate the neural activity associated with the detection of conflict, I examined event-related BOLD activation in response to CI trials relative to II trials in bilinguals and monolinguals. A *t*-contrast comparing CI to II trials was computed for each subject and then submitted to group level analyses. First, a whole-brain analysis with a minimum cluster threshold of 5 voxels for the CI>II contrast was conducted separately for bilinguals and monolinguals to examine the networks involved in conflict detection in each language group.

Table 6

*Regions of Activation for CI>II by Language Group*

| Regions of activation | [x , y, z] | *t*-value |
|---|:---:|:---:|
| *Bilinguals* | | |
| *PFC* | | |
| L. anterior vlPFC (BA47) | [-32, 22, -14] | 4.47 |
| R. vlPFC (BA45) | [54, 28, 30] | 3.92 |
| R. vlPFC (BA44) | [58, 20, 30] | 3.88 |
| R. insula | [30, 16, -12] | 4.25 |
| | | |
| *Medial PFC* | | |
| R. anterior mid-cingulate | [8, -10, 32] | 4.85 |
| R. SMA (BA32) | [10, 24, 48] | 3.96 |
| R. superior orbital frontal | [18, 48, -14] | 3.89 |
| | | |
| *Parietal lobe* | | |
| L. precuneus (BA7) | [-8, -72, 38] | 3.85 |
| | | |
| *Temporal lobe* | | |
| R. inferior temporal gyrus (BA20) | [58, -26, -20] | 4.42 |
| R. middle temporal gyrus | [50, -44, 8] | 4.08 |
| | | |
| *Cerebellum* | | |
| L. anterior cerebellum | [-10, -28, -18] | 3.78 |
| R. anterior cerebellum | [10, -38, -18] | 4.69 |
| | | |
| *Monolinguals* | | |
| *PFC* | | |
| L. precentral (BA6) | [-42, -4, 38] | 5.28 |
| R. precentral (BA9) | [46, 6, 38] | 4.58 |
| R. primary motor cortex (BA4) | [38, -18, 56] | 4.52 |
| | | |
| *Medial PFC* | | |
| L. anterior cingulate | [-10, 8, 40] | 4.19 |
| L. SMA (BA32) | [-6, 4, 46] | 4.94 |
| R. anterior cingulate | [8, 8, 32] | 4.11 |
| R. SMA (BA24) | [6, 2, 48] | 4.89 |
| | | |
| *Parietal lobe* | | |
| L. inferior parietal | [-42, -36, 44] | 4.69 |
| R. postcentral gyrus (BA3) | [42, -24, 42] | 4.34 |
| | | |
| *Sub-cortical* | | |
| R. caudate head | [10, 10, 6] | 3.95 |

*Note*. MNI coordinates for the peak activation in each cluster are reported ($p < .0001$, uncorrected).

As reported in Table 6, bilinguals exhibited significantly increased prefrontal activity ($p < .0001$, uncorrected) for CI>II in the left anterior vlPFC (BA47), right vlPFC (BA44/45), right insula, right anterior mid-cingulate, right supplementary motor area (SMA; BA32), and right superior orbital frontal cortex. They also exhibited significantly increased activity in the left precuneus (BA7), right middle and inferior temporal gyri, and bilaterally in the anterior cerebellum (see Table 6; Figure 6). There were no regions where bilinguals exhibited significantly decreased activation for CI relative to II trial sequences. For the same CI>II contrast, monolinguals exhibited significant increases in prefrontal activity ($p < .001$, uncorrected) in the left and right precentral cortex (BA6; BA9), right primary motor cortex (BA4), and bilaterally in the anterior cingulate and SMA (BA32; BA24). They also demonstrated significantly increased activity in the left inferior parietal lobule, right post-central gyrus (BA3), and the head of the right caudate (see Table 6; Figure 6). There were no regions where monolinguals had significant decreases in activation for CI relative to II trial sequences.
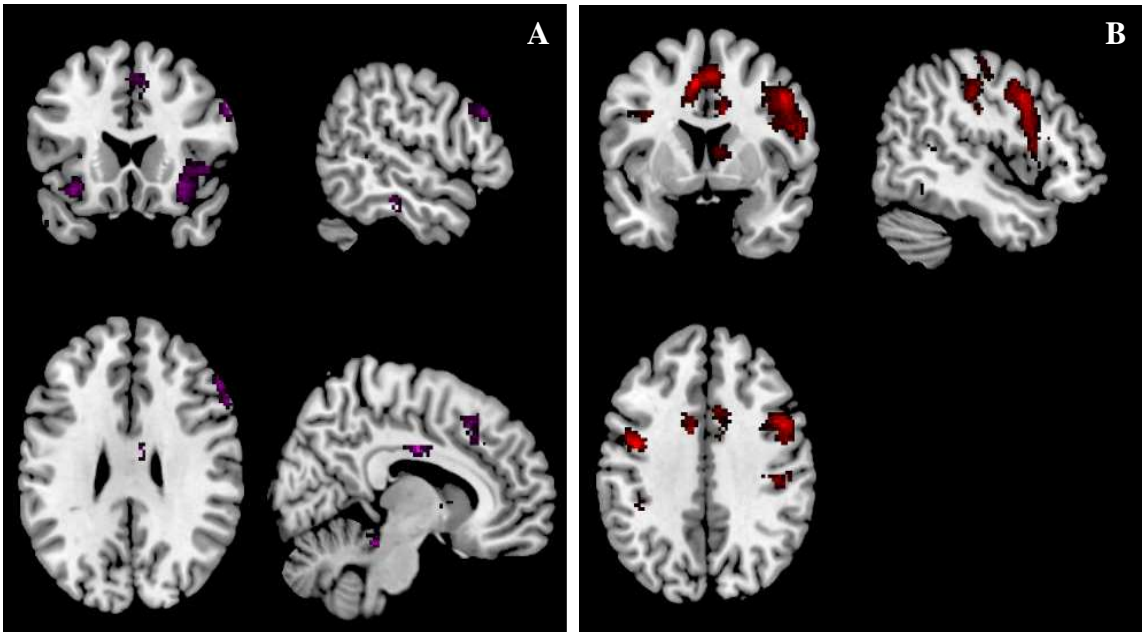
*Figure 6. Significant activation for CI-II (p < .001, uncorrected) in each language group.* **(A)** Bilinguals demonstrate significantly increased activity in the L. anterior vlPFC, R. vlPFC, R. insula, R. inferior and middle temporal lobe, R. SMA, and R. anterior mid-cingulate. **(B)** Monolinguals demonstrate significantly increased activity in the L. precentral cortex, L. and R. anterior cingulate and SMA, R. precentral cortex, R. primary motor cortex, R. post-central gyrus, and R. caudate.

To examine the effect of language group on conflict detection, I conducted a two-sample *t*-test comparing the CI>II effect in bilinguals and monolinguals. As can be seen in Figure 7, a whole-brain analysis with a 5-voxel minimum cluster threshold revealed that bilinguals had greater activation for CI>II than monolinguals ($p < .001$, uncorrected) in the left caudate [-6, 18, 14], left anterior vlPFC (BA47; [-34, 24, -12]), and right superior temporal pole [42, 10, -22], whereas monolinguals had greater activation than bilinguals ($p < .001$, uncorrected) in the left precentral gyrus (BA6; [-42, -4, 36]). To better understand the patterns underlying these group differences, I defined functional regions-of-interest (ROIs) from the voxels activated above threshold ($p < .001$, uncorrected) by the CI>II contrast for bilinguals relative to monolinguals and vice versa. Then, mean beta estimates were computed separately

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for CI trials and II trials in these ROIs for each group (see Table 7). This calculation

helps determine whether observed CI>II activations are due to increased positive

activation on CI relative to II trials or decreased negative activation (i.e., decreased

suppression) on CI relative to II trials.
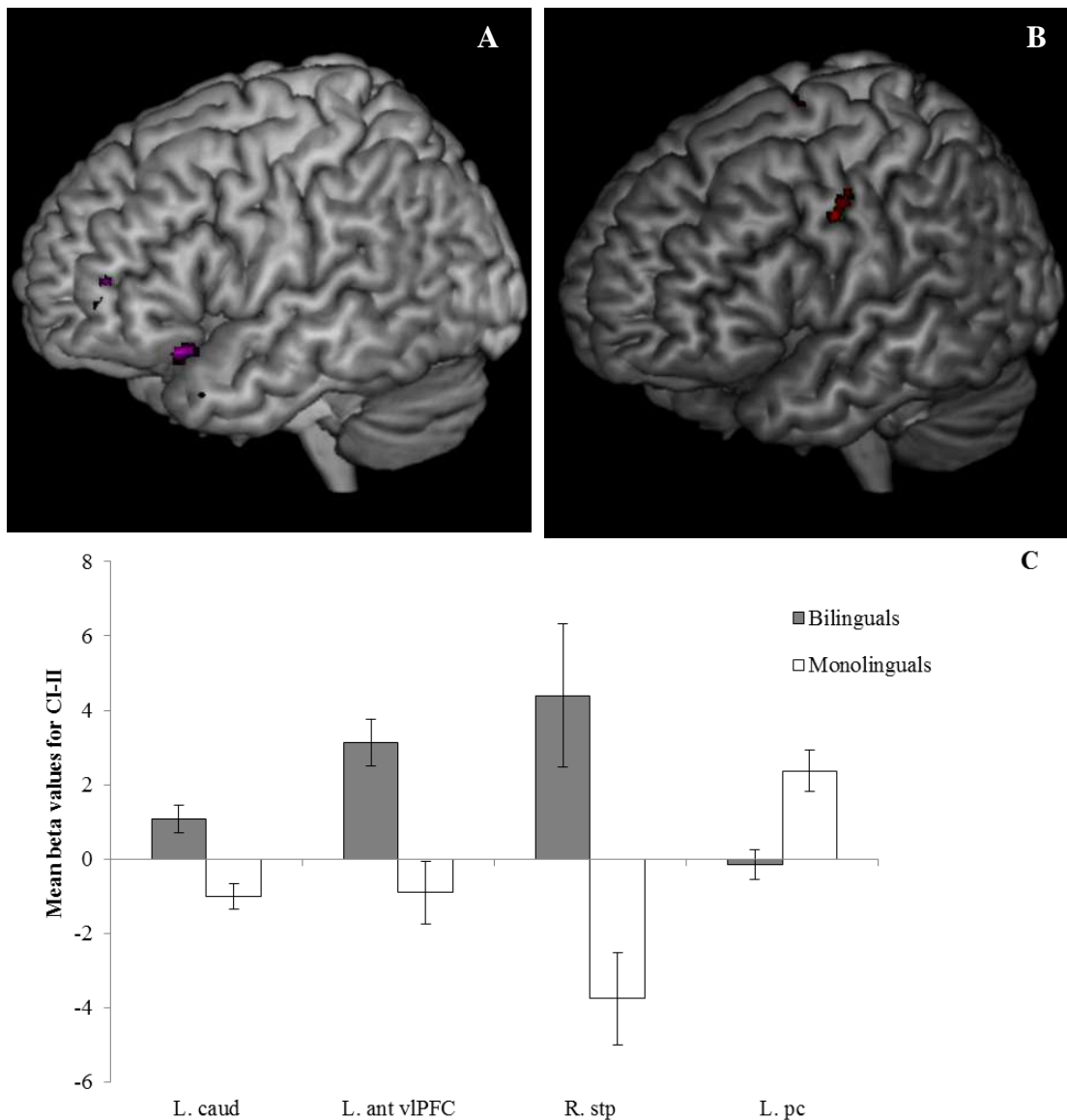


*Figure 7. Significant group differences in activation for CI-II (p < .001, uncorrected).* **(A)** Bilinguals demonstrate increased activity in the left anterior vlPFC relative to monolinguals (purple). **(B)** Monolinguals demonstrate increased activity in the left precentral cortex (BA6) relative to bilinguals (red). **(C)** Mean beta values for CI-II in bilinguals and monolinguals for all regions demonstrating significant group differences (p < .0001. Error bars represent standard error. L. caud = left caudate; L. ant vlPFC = left anterior vlPFC; R. stp = right superior temporal pole; L. pc = left precentral.

As can be seen in Table 7, monolinguals exhibited increased positive activation in the left precentral cortex on CI relative to II trials, reflecting greater recruitment of these regions during conflict detection. In contrast, bilinguals' activation did not change across CI and II trials in this region, indicating that they do not recruit the left precentral cortex for conflict detection. Both groups showed negative activation in the left caudate; however, monolinguals exhibited more suppression for CI relative to II trials, whereas bilinguals demonstrated the reverse pattern. A similar pattern emerged in the right superior temporal pole, where monolinguals exhibited greater suppression for CI relative to II trials, but bilinguals suppressed this region for II relative to CI trials. This indicates that bilinguals and monolinguals may both suppress the left caudate and right superior temporal pole during conflict monitoring, but at different stages, with bilingual suppression *increasing* from CI to II trials and monolingual suppression *decreasing* from CI to II trials. Finally, while bilinguals demonstrated increased suppression of the left anterior vlPFC on II versus CI trials, monolinguals showed equivalent levels of negative activation during CI and II trials.

Table 7

*Mean Beta Values (and Standard Error) for BOLD activity on CI and II trials in ROIs*

| Language group | Trial Type | |
| --- | --- | --- |
| | CI | II |
| *Left caudate* | | |
| Bilingual | -2.65 (0.93) | -3.52 (0.84) |
| Monolingual | -2.78 (0.79) | -1.99 (0.95) |
| *Left anterior vlPFC* | | |
| Bilingual | -0.28 (1.46) | -3.50 (1.72) |
| Monolingual | -4.97 (2.77) | -4.43 (2.36) |
| *Right superior temporal pole* | | |
| Bilingual | -8.16 (2.52) | -11.95 (2.51) |
| Monolingual | -6.63 (2.94) | -3.45 (2.78) |
| *Left precentral cortex* | | |
| Bilingual | 4.16 (1.55) | 3.94 (1.50) |
| Monolingual | 6.28 (1.45) | 4.41 (1.46) |

## *Discussion*

Coupling the behavioral and brain-activation data, these results generally support the conflict monitoring account of the bilingual advantage. As predicted, bilinguals and monolinguals differed in their conflict detection abilities. Specifically, monolinguals had poorer accuracy after congruent trials than after incongruent trials, whereas bilinguals exhibited equally good accuracy after both trial types. Monolinguals may have relative difficulty with the conflict detection stage of conflict monitoring, but achieve better performance after conflict detection by reactively recruiting cognitive control; bilinguals, in contrast, appear to be prepared to resolve both initial and subsequent conflicts proactively, suggesting superior conflict detection.

Bilinguals and monolinguals also demonstrated different patterns of neural activation for initial conflict trials relative to subsequent conflict trials, providing

potential mechanisms for bilinguals' apparently improved conflict detection. Monolinguals, but not bilinguals, recruit the left precentral cortex (BA6) during conflict detection, perhaps reflecting increased conflict experienced by monolinguals on these trials. Indeed, this region, also known as the pre-premotor cortex, is typically activated when different perceptual features correspond to incompatible responses, with activation increasing as the number of relevant features, and thus competition, increases (Badre & D'Esposito, 2007; Koechlin & Summerfield, 2007). In other words, this portion of BA6 seems to respond to conflict between mental representations, such as deciding whether the concept "blue" or "red" is more relevant when presented with the word "blue" written in red ink. In the present study, monolinguals recruited this region during conflict detection to a greater extent than bilinguals while simultaneously demonstrating relatively poorer accuracy on trials requiring conflict detection. Note that since the BOLD signal was examined for correct trials only, this result indicates differential activation between the language groups during successful conflict resolution. Thus, monolinguals' increased engagement of the left precentral cortex may reflect a greater expenditure of effort to resolve competition between features.

Conflict-detection-related activity was greater in bilinguals than monolinguals in the left caudate. Interestingly, the left caudate is also engaged by switching languages during production, particularly for trials that externally cue a language-switch compared to trials that cue the language already-in-use (Abutalebi et al., 2012; 2013). In monolinguals, intraoperative stimulation of the dominant-hemisphere caudate during picture-naming induces repetition of the previous item name,

suggesting that the caudate is involved in inhibiting previously relevant representations (Robles, Gatignol, Capelle, Mitchell, & Duffau, 2005). The role of this region in language-switching coupled with its relatively increased recruitment by bilinguals suggests that bilinguals may rely on the neural system underlying language-switching to enact conflict detection. Reliance on this practiced network may enable better conflict resolution upon first encountering conflicts, as bilinguals achieved equivalently high accuracy on CI and II trials. If the left caudate is indeed responsible for inhibiting previously relevant representations, it may help implement both language-switching and conflict detection: in language-switching, the caudate may inhibit representations from the previously relevant language, whereas in conflict detection, the caudate may help inhibit attention to the word meaning (which is potentially relevant on a previous non-conflict trial).  Importantly, whereas bilinguals exhibited *increased* activation for CI relative to II trials in the left caudate, monolinguals exhibited *decreased* activation for the same contrast. This may indicate that bilinguals and monolinguals are engaging the left caudate at different times, reflecting proactive control in bilinguals (demonstrated by successful performance on initial conflicts) and reactive control in monolinguals (demonstrated by more successful performance on subsequent conflicts).

Bilinguals also recruited the right superior temporal pole for conflict detection to a greater extent than monolinguals. Specifically, whereas monolinguals reactivated the right superior temporal pole on II trials relative to CI trials, bilinguals showed the reverse pattern. This region is considered to be part of the "salience network," which is responsible for orienting towards novel events and engaging cognitive control

(Tian, Qin, Liu, Jiang, & Yu, 2013), and damage to this region produces deficits in disengaging attention (Gandola et al., 2013). Bilinguals' suppression of this region following conflict detection suggests that they oriented to the conflict on the initial conflict trial; in contrast, monolinguals seem to demonstrate orientation to conflict later in the trial sequence, activating this region more strongly on subsequent conflict trials.

Finally, bilinguals demonstrated increased conflict-detection-related activity relative to monolinguals in the left anterior vlPFC. Here, monolinguals exhibited more suppression of the left anterior vlPFC than bilinguals on CI trials, but whereas monolinguals' suppression remained constant across CI and II trials, bilinguals' deactivate this region on II relative to CI trials. This finding implicates the left anterior vlPFC in bilinguals' relatively superior conflict detection, because monolinguals but not bilinguals suppress this area on CI trials. According to Badre and colleagues (2005), this region is responsible for the controlled retrieval of semantic information in situations when environmental cues are insufficient to support retrieval. In other words, the left anterior vlPFC comes online to facilitate retrieval when the association between external cues and semantic knowledge is relatively weak. This region has also been implicated in the maintenance and retrieval of task goals, as it is engaged by multidimensional stimuli associated with multiple response rules (Crone, Wendelken, Donohue, & Bunge, 2006). In the present study, the association between the font color and the relevant color representation, as well as the task goal to respond to the font color, may be relatively weak on CI trials because the previous trial did not require participants to access the font color representation to

respond correctly. Thus, on CI trials, perceptual cues from the font color may be insufficient to retrieve the appropriate color representation and response rule. The finding that bilinguals have greater left anterior vlPFC activation than monolinguals on these trials may indicate that bilinguals are using top-down control to retrieve the goal-relevant information, leading to their increased accuracy following congruent trials. Importantly, bilinguals employ this control during initial conflict detection, again suggesting that they proactively prepare to handle potential information conflicts.

One question raised by the present results is why bilinguals' improved conflict detection was associated with *increased* rather than *decreased* recruitment of the left caudate, the left anterior vlPFC, and the right superior temporal pole, relative to monolinguals. This result is potentially inconsistent with previous evidence showing that bilinguals' reduced cost in task-switching was associated with decreased activation in cognitive control regions (Gold et al., 2013). However, these apparently contradictory findings come from different age groups, which may impact the relationship between functional activation and performance. Indeed, prior research has observed an interaction between the effects of age and executive function demands on neural activity in the bilateral vlPFC and dlPFC, such that in young adults, activity increased as goal-maintenance and shifting demands increased, but in older adults, this pattern reversed (Hagen et al., 2014). Moreover, the relationship between activation in the right vlPFC and performance on the executive function task changed as a function of age (Hagen et al., 2014). This suggests that the patterns of neural activity that subserve cognitive processes may change with age, meaning that

the relationship between activation and performance on cognitive control tasks is not necessarily expected to be the same in younger and older adults.

The present results suggest that bilinguals enjoy enhanced conflict detection abilities, perhaps as a result of increased reliance on the neural resources involved in language-switching, namely, the left caudate. However, conclusions regarding the overlap between the mechanisms underlying language-switching and conflict detection are limited in the present study, which did not attempt to co-localize activation related to both conflict detection and language-switching. Future studies should examine both procedures within the same group of subjects to determine whether they actually engage overlapping regions of cortex.

I observed a bilingual advantage in the conflict detection stage of conflict monitoring. This finding supports the conflict monitoring account of the bilingual advantage and opens the door to future research examining online regulation of cognitive control in bilinguals and monolinguals. Moreover, bilinguals exhibited differential patterns of neural activation in regions involved in conflict control, including increased activation of the left anterior vlPFC and decreased activation of the left precentral cortex. This, coupled with bilinguals' increased recruitment of the left caudate during conflict detection, supports the idea that practice switching between languages improves conflict monitoring in bilinguals, because it demonstrates that bilinguals employ similar neural resources for language-switching and conflict detection. Interestingly, monolinguals exhibited greater activity for *subsequent* than *initial* conflicts in the left caudate, whereas bilinguals showed the reverse pattern, suggesting that monolinguals and bilinguals may be recruiting

cognitive control at different times, with bilinguals engaging it proactively and monolinguals reactively. Additionally, during conflict detection, bilinguals but not monolinguals proactively engaged the left anterior vlPFC, which may be involved in retrieval of task-relevant information. Taken together, these results support the notion that life-long bilingualism may act as a naturalistic form of cognitive control training, increasing the ability to monitor input for conflict and the readiness to resolve new or unexpected conflicts.

Interestingly, bilinguals' apparent behavioral advantage in conflict detection in Experiment 3 paralleled the advantage found in Experiment 2. In both experiments, bilinguals exhibited equivalently high accuracy regardless of preceding trial type, whereas monolinguals' accuracy declined following congruent trials, suggesting that monolinguals have difficulty detecting initial conflicts. This replication is especially noteworthy given the many methodological differences between the two experiments.

The conflict adaptation paradigm used in Experiment 3 in many ways placed a greater demand on cognitive resources than the version used in Experiment 2. First, Experiment 3 was conducted in an MR-environment with continuous scanner noise. Another side effect of the MR-environment is that stimulus presentation was jittered in Experiment 3, but constant in Experiment 2. This may have reduced the predictability of when stimuli would occur. Finally, Experiment 3 had four possible response options and only contained response-eligible trials, whereas Experiment 2 only had three response options and contained both response-eligible and ineligible trials. Thus, participants in Experiment 3 had to maintain more color-response associations in memory, while having to resolve stronger conflicts (as response-

eligible trials typically induce greater conflict than response-ineligible trials; Milham et al., 2001, 2003). Despite these differences in experimental paradigms, bilinguals remained unaffected by preceding trial type in both experiments, whereas monolinguals' accuracy was degraded following congruent trials in both experiments.

Although the bilingual advantage appeared to be selective for conflict detection in Experiments 2 and 3, these results do not preclude the possibility that bilinguals also possess an advantage in adaptively adjusting cognitive control. Bilinguals and monolinguals both performed near ceiling (over 90% correct) on II trials; thus, it may not be possible to observe a bilingual advantage in conflict adaptation in the present paradigm. Indeed, ceiling effects are a common obstacle for studies investigating the bilingual advantage, as performance on the cognitive control tasks typically used to assess it can be quite high (see e.g., Bialystok et al., 2004). A challenge for future research is therefore to examine bilinguals' and monolinguals' conflict monitoring abilities on more difficult cognitive control tasks.

One of the aims of Experiment 4 was to investigate the robustness of the effect of bilingualism on conflict monitoring by doing just this. Experiment 4 compares performance of bilinguals and monolinguals on a two difficult tasks that require frequent conflict detection: a recognition memory task involving conflict on "lure" items that had been seen recently but are irrelevant to the current memory judgment and a sentence processing task involving recovery from misinterpretation on temporarily ambiguous sentences. Importantly, this study also extends the investigation of the bilingual advantage to linguistic tasks. Most demonstrations of the bilingual advantage in cognitive control have used non-linguistic tasks (e.g.,

Flanker, Simon). These findings are compelling and suggest that the bilingual advantage is domain-general, but it is important to show that the advantage also emerges with linguistic material, because the alleged source of the advantage is bilinguals' systematic control of two language systems. As described previously, a growing body of literature demonstrates that syntactic ambiguity resolution relies on the same cognitive control resources as non-syntactic conflict resolution (January et al., 2009; Novick et al., 2005; 2009; 2013). Indeed, in Chapter 2, I showed that processing syntactic ambiguity resulted in faster and more accurate conflict resolution on subsequent trials, indicating that the domain-general conflict monitoring system applies to the syntactic domain. Thus, if bilinguals have an advantage in conflict monitoring, it is expected to transfer to sentence processing when a subset of sentences contain temporary syntactic ambiguities.

# Chapter 5:  Experiment 4[6]

*Overview*

Despite the evidence (Bialystok, 2010; Bialystok et al., 2004, 2009; Costa et al., 2008, 2009; Hernández et al., 2010; Martin-Rhee & Bialystok, 2008; but see also Hilchey & Klein, 2011; Paap & Greenberg, 2013) supporting a bilingual advantage in conflict monitoring, there are still several unanswered questions regarding the nature, specificity, and extent of this advantage. In particular, few studies have examined whether the bilingual advantage cascades into language processing. As the supposed source of bilinguals' cognitive advantage is the systematic control of two languages, these benefits should transfer to the linguistic domain. It is also unclear how robust the bilingual advantage is to changing task demands, especially given reports of a lack of uniformity in cross-task bilingual performance: Does the advantage emerge consistently across tasks tapping shared cognitive control functions? Do monolinguals 'catch up' to bilinguals during cognitive control practice? Experiment 4 aims to address these issues by testing whether healthy, young adult bilinguals outperform monolinguals on a reading task involving syntactic ambiguity resolution—a cognitive control task in the linguistic domain—both before and after

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[6] Portions of this work have been submitted for publication and are currently under review (Teubner-Rhodes, S., Mishler, A., Corbett, R., Andreu, L., Sanz-Torrent, M., Trueswell, J., & Novick, J. The bilingual advantage: Conflict monitoring, cognitive control, and garden-path recovery. *Journal of Memory and Language.*)

brief practice with a recognition-memory task that theoretically taps shared conflict-resolution functions.

How Robust is the Bilingual Advantage?

Inconsistencies across the bilingualism literature call into question the robustness of the effect of bilingualism on cognitive control. One problem is that monolinguals often 'catch up' to bilinguals with a small amount of practice (see e.g., Bialystok et al., 2004; Costa et al., 2009). If one session of practice on the Simon task is equivalent to a lifetime of bilingual language experience, then the effect of bilingualism on cognitive control seems rather weak—perhaps bilinguals reach a limit on cognitive control capacity and are unable to improve further. Yet accuracy on typical cognitive control tasks (e.g., Simon, Flanker) is quite high (e.g., greater than 97%; Bialystok et al., 2004); it may be impossible to observe continued improvements because bilinguals are already at ceiling. The current study aims to determine whether monolinguals and bilinguals benefit differentially from cognitive control practice by administering tasks with initially low performance, allowing for greater practice-related changes.

Another issue is that a bilingual advantage is observed in some experiments but not in others, with no apparent pattern to its (non-)occurrence (Hilchey & Klein, 2011; Paap & Greenberg, 2013). Indeed, Paap and Greenberg (2013) assessed the stability of bilingual benefits by administering within-subjects a variety of executive function tasks (Simon, Flanker, Antisaccade, Ravens Progressive Matrices, and Color-Shape Switching) to healthy young monolinguals and bilinguals. As often as not, bilinguals exhibited a nominal *disadvantage* relative to monolinguals. The

authors acknowledged, however, that correlations between these different tasks are rather weak; thus, the inconsistency in bilingual performance may have been because the tasks largely assessed different components of executive control. A current challenge for bilingual research is to demonstrate that a bilingual advantage occurs consistently across tasks that tap a common cognitive control resource. To this end, I test whether bilingual benefits manifest in sentence processing when conflict monitoring demands are high, and if this performance can be tied to conflict-monitoring abilities in a non-syntactic domain.

Do the Effects of Bilingualism Cascade into On-line Sentence Processing?

Surprisingly, most investigations of bilingualism's effects on cognitive control have been limited to non-linguistic tasks. If controlled use of two languages enhances cognitive control, then bilingualism must impact linguistic cognitive control performance as well. One difficulty with testing this is that bilinguals exhibit *slower* lexical access in each of their languages (Gollan, Montoya, Cera, & Sandoval, 2008; Ivanova & Costa, 2008; Sandoval, Gollan, Ferreira, & Salmon, 2010), perhaps reflecting increased competition across two constituent lexicons. Yet little is known about the effects of bilingualism on sentence processing after lexical access has occurred.  If bilingualism improves conflict monitoring, then I believe that—despite their apparent disadvantages in lexical access—bilinguals should enjoy a sentence processing advantage when monitoring demands are high—namely, when the environment necessitates checking for syntactic conflict and potentially frequent misinterpretation.

This prediction stems directly from evidence that general-purpose cognitive control functions deploy under language processing conditions involving ambiguity (January et al., 2009; Novick et al., 2005, 2009; Ye & Zhou, 2009). In particular, during sentence processing, parsers may recruit cognitive control to revise misinterpretations that arise when multiple, conflicting evidential sources lead them to an incorrect syntactic analysis (Novick et al., 2005). According to constraint-based models of parsing, as readers and listeners perceive input, they rapidly consult multiple, probabilistic sources of information (e.g., lexico-syntactic cues and visual context) to make real-time predictions about sentence meaning (MacDonald, Pearlmutter, & Seidenberg, 1994; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Trueswell, Tanenhaus, & Garnsey, 1994). In most cases, these evidential sources converge and the initially favored parse ultimately turns out to be correct. Such sentences should not require conflict resolution even if other parses were initially available, but disfavored. Sometimes, however, the parser's early interpretation conflicts with evidence that arrives later on, which can result in processing difficulty (known as the "garden-path effect"). This forces parsers to resolve the conflict and revise their incorrect analysis. Under such conditions, cognitive control may serve to rein-in initial misinterpretations and recover the intended meaning (Novick et al., 2005; Ye & Zhou, 2009). Accordingly, if bilingualism enhances cognitive control resources, then it should also improve performance on sentence processing tasks involving syntactic ambiguity.

But how exactly should the effects of bilingualism manifest in syntactic ambiguity resolution? We consider this question in view of bilinguals' apparent

conflict monitoring advantages on non-linguistic tasks (Costa et al., 2009; Hilchey &

Klein, 2011). Parsers routinely use multiple evidentiary sources to assign meaning,

but only seem to rely on cognitive control for ambiguous sentences invoking

competing interpretations (January et al., 2009; Novick et al., 2009). Typical

language contexts often contain ambiguous *and* unambiguous sentences, so parsers

must constantly look out for contradictions between their initial interpretation and

subsequent input as they cannot know in advance when their initial parse will turn out

to be wrong. If bilinguals are better at conflict monitoring, then they should be better

at detecting ambiguities and recruiting cognitive control to revise misinterpretations,

but also at using converging information sources to efficiently arrive at the correct

interpretation in unambiguous sentences. Thus, bilinguals should outperform

monolinguals on ambiguous *and* unambiguous sentences in linguistic environments

that contain both—that is, under conditions when they have to monitor for potential

misinterpretations.

Relatively few studies have examined the effects of bilingualism on sentence

processing. An important exception, however, is an investigation of auditory sentence

comprehension in bilinguals and monolinguals, which found that bilinguals had

higher comprehension accuracy than monolinguals on "target" sentences with

atypical word orders, but only when they had to ignore simultaneously-presented

"distracter" sentences (Filippi, Leech, Thomas, Green, & Dick, 2012). This result

suggests that bilinguals are better at suppressing interfering linguistic information

than monolinguals. However, the bilinguals in this study had primarily acquired their

second language after age 10—it is plausible then that they became fluent in a second

language *because* they possessed superior linguistic (or cognitive control) abilities. Moreover, because the distracter sentences always had a different word order than the target sentences, participants might fail to understand the targets simply by mixing-up distracter and target information. It remains uncertain whether bilingualism actually improves parsing abilities—in the present study, parsing abilities are investigated in early bilinguals who acquired both their languages prior to age 10. It is unlikely that such individuals become bilingual as a result of superior cognitive control, because, by and large, they learn two languages because their particular environmental circumstance involves simultaneous (or nearly simultaneous) input of two language systems.

Experiment 4 addressed three open questions in the bilingualism literature. First, do the effects of bilingualism on cognitive control emerge consistently across different tasks with shared conflict-resolution demands? Second, does practice on a cognitive control task benefit bilinguals and monolinguals differentially? Finally, does bilingualism affect sentence processing when ambiguity/conflict is present?

Study Overview

I tested Spanish-Catalan bilinguals and Spanish monolinguals on a reading task involving temporary syntactic ambiguity both before and after practice on either a high- or no-conflict version of an N-back recognition-memory task (where N is 3; see Figure 8 for a study-design schematic). For consistency, the entire experiment was conducted in Spanish for both language groups. The pretest/posttest design allowed a comparison of baseline sentence processing abilities and the effects of cognitive control practice in bilinguals and monolinguals. It also allowed me to test

whether the effect of bilingualism emerges consistently across ostensibly distinct

cognitive control tasks that nevertheless share the need to detect information-conflict.
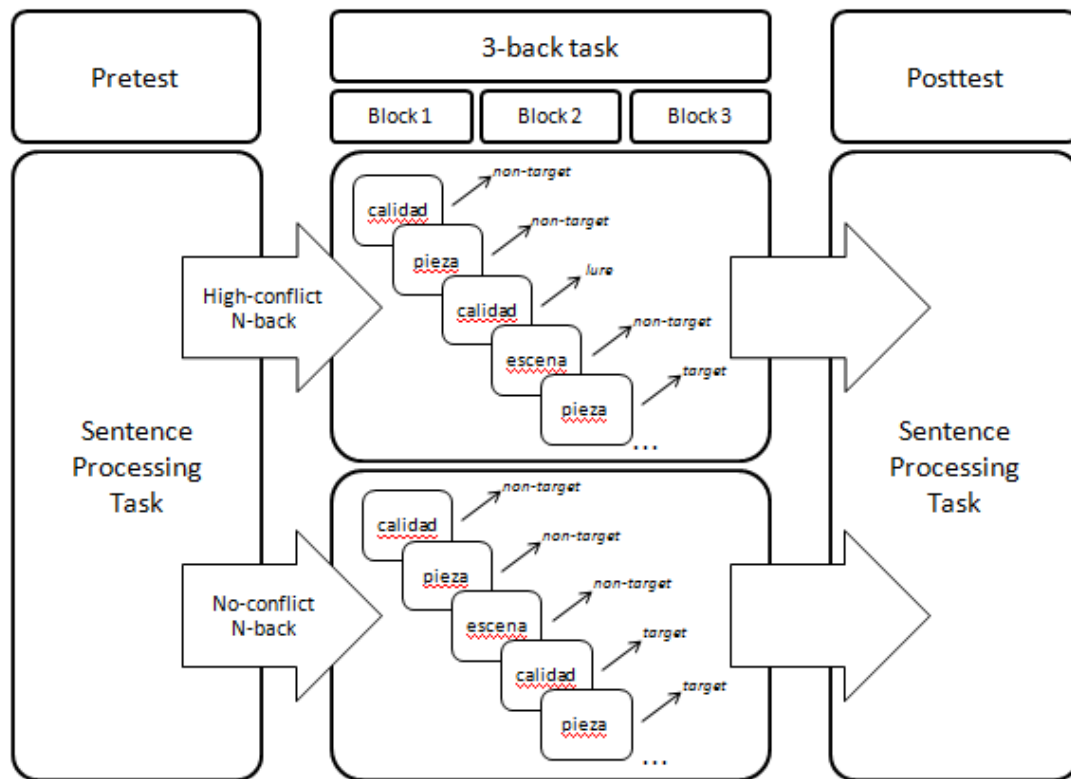


*Figure 8. Schematic of the study design.* Participants completed a sentence-processing task before and after performing either a high- or no-conflict version of the N-back task. Both N-back versions are depicted: while the no-conflict task (bottom panel) contained only target trials that were 3-back matches and non-target trials that had not appeared before, the high-conflict task (top panel) also included lure trials, items that had appeared before but not in the target 3-back position, thus tapping conflict detection between highly familiar but non-target stimuli. For instance, in the high-conflict task, the second "calidad" is a lure, because it matches the item that had occurred 2 (rather than 3) items previously. In contrast, the same item appears as a target, or 3-back match, in the no-conflict task, which did not include any lures.

I specifically chose recognition-memory and sentence parsing tasks because

they appear to recruit a common cognitive control mechanism (Novick et al., 2005).

In this study's version of the N-back task, subjects view single words presented in

sequence and identify whether the current word matches the one shown three trials

back. The high-conflict N-back included *lures*, stimuli that induce a familiarity bias

and require cognitive control to arrive at the correct position-based response
(Burgess, Gray, Conway, & Braver, 2011). In contrast, the no-conflict version omits
lure trials, so successful performance only requires recognition memory.

The high-conflict N-back is demanding and captures individual differences in
performance on other cognitive control tasks, like matrix reasoning (Jaeggi,
Buschkeuhl, Jonides, & Perrig, 2008). Crucially, behavioral improvements during
long-term training on this task predict gains in garden-path recovery (Novick,
Hussey, Teubner-Rhodes, Harbison, & Bunting, 2013). Moreover, conflict trials on
N-back and other, similar recognition-memory tasks (Gray, Chabris, & Braver, 2003;
Jonides & Nee, 2006) activate the same neural regions as syntactic ambiguity
resolution and prototypical conflict-control tasks like Stroop (January et al., 2009; Ye
& Zhou, 2009). Thus, the high- but not the no-conflict N-back engages cognitive
control resources that are also recruited when processing garden-path sentences.

My predictions were as follows. First, I hypothesized that performance on N-
back would correlate with sentence processing performance, reflecting shared
variance in subjects' cognitive control abilities. Second, I hypothesized that bilinguals
would outperform monolinguals on the sentence processing and the high-conflict N-
back tasks: bilinguals should be faster and more accurate than monolinguals on both
conflict (ambiguous sentences and lures on N-back) and non-conflict (unambiguous
and filler sentences and non-lures on N-back) trial types. However, on the no-conflict
N-back task, where conflict monitoring is unnecessary, I predicted that bilinguals and
monolinguals would perform equivalently. Additionally, because only the high-
conflict N-back group practiced implementing cognitive control, I expected that

improvements in syntactic ambiguity resolution from pretest to posttest would be mediated by N-back task version, such that participants in the high-conflict group would show greater improvements than those in the no-conflict group. Finally, I predicted that *both* bilinguals and monolinguals should benefit from brief cognitive control practice on the high-conflict N-back. Specifically, because bilinguals should not start at ceiling on this task (average accuracy is typically between 60 and 70%; see Kane, Conway, Miura, & Colflesh, 2007), they are expected to improve with practice, preventing monolinguals from 'catching up.' Indeed, if bilinguals have superior conflict monitoring, then they may achieve greater gains than monolinguals, due to more flexible adjustments in cognitive control.

*Method*

Participants

Participants included healthy adult balanced Spanish-Catalan bilinguals (N=59; 7 males; $M_{age}$=20.78, $SD_{age}$=3.38) and Spanish monolinguals (N=51; 12 males; $M_{age}$=26.51, $SD_{age}$=5.94) recruited from the University of Barcelona community. Participants in each language group were randomly assigned to either the high- or no-conflict N-back condition. The final distribution included 32 high-conflict bilinguals (4 males; $M_{age}$=20.53, $SD_{age}$=3.15), 27 no-conflict bilinguals (3 males; $M_{age}$=21.07, $SD_{age}$=3.67), 26 high-conflict monolinguals (6 males; $M_{age}$=25.54, $SD_{age}$=5.39) and 25 no-conflict monolinguals (6 males; $M_{age}$=27.52, $SD_{age}$=6.42).

I did not initially collect information about subjects' socioeconomic status (SES); however, recent studies debate whether (see e.g., Morton & Harper, 2009) or

not (see e.g., Bialystok, 2009; Engel de Abreu, Cruz-Santos, Tourinho, Martin, & Bialystok, 2012) these factors influence the bilingual advantage. Thus, one-and-a-half years after the study, I invited participants to complete an online survey about their parents' income, occupations, and education levels. The subset of participants who responded (n=40) was evenly distributed across the two language and two conflict groups (high-conflict bilinguals: n=10; no-conflict bilinguals: n=11; high-conflict monolinguals: n=10; no-conflict monolinguals: n=9). I scored parental occupations from 1-9 on the 9-point Hollingshead Occupational Status Scale (Hollingshead, 1975). Then, I generated a composite score for each subject to determine their overall SES; composite measures of parental occupation, education, and income are more stable than income alone (McLoyd, 1998) and have previously been used to examine SES-related differences in cognitive functioning (Noble, Norman, & Farah, 2005). Because several subjects (n=9) chose not to report their parents' average annual income, the composite measure was based on parental education and parental occupations. SES composite scores from 1-3 were assigned based on the criteria in Table 8, where 1 represents the lowest SES and 3 the highest. For the majority of subjects (n=31), the scores derived from the education and occupation criteria were in agreement. If, however, these criteria indicated different scores for a particular subject, then the two scores were averaged—for example, if a subject scored a 1 for parental education and a 2 for parental occupation, then his composite SES score would be a 1.5.

To evaluate whether SES differed between the four groups, I conducted a Kruskal-Wallis rank sum test on SES composite scores. This non-parametric test was

chosen because the SES composite scores are ordinal data based on self-assessment

ratings (see Table 8). The distributions of SES composite scores did not significantly

differ across the groups ($H(3)=0.71$, $p=.87$), suggesting that, among those subjects

who provided SES data, SES was comparable for high-conflict bilinguals, no-conflict

bilinguals, high-conflict monolinguals, and no-conflict monolinguals.

Table 8

*Parental Education and Occupation Criteria for SES Composite Scores*

| SES score | Parental education criteria | Parental occupation criteria |
|---|---|---|
| 1: low SES | Highest parental education level is no more than high school diploma or vocational equivalent | Highest parental occupation is 4 or less on Hollingshead scale |
| 2: middle SES | At least one parent has an education between an advanced vocational and a college degree | Highest parental occupation is 4-6 on Hollingshead scale |
| 3: high SES | At least one parent has a college degree or better | Highest parental occupation is 7 or greater on Hollingshead scale |

All subjects were given the option of receiving payment (12 Euros) or course

credit for their participation. More bilinguals (n=56) chose course credit than

monolinguals (n=15); however, because subjects were allowed to choose, it is

unlikely that any observed group differences could be ascribed to motivational factors

related to compensation. Also, despite the gender imbalance in the experiment,

females accounted for the same high distribution of participants across the two

language groups and across the two versions of the N-back task.

Language status was verified using language questionnaires borrowed from

Appendix B in Costa et al. (2009). Bilinguals were included if: their first language

was Spanish, Catalan, or both; they had some exposure to both Spanish and Catalan

before or during primary school; they continued using both languages through adulthood; they used both languages approximately equally during either childhood or adolescence; they reported at least "sufficient proficiency" in speaking, writing, listening and reading in both languages; *and* they were not fluent in a third language. Monolinguals were included if: their first language was Spanish, and they had little exposure to any other languages before secondary school; they used only Spanish at least three-fourths of the time in adolescence; *and* they were not fluent in speaking or listening comprehension in any language other than Spanish. An additional 25 subjects participated, but were dropped from analyses because they did not fit into either language group (n=19), because they were less than 75% accurate on filler sentences or non-target N-back trials (n=5; 2 bilinguals), or because of computer error (n=1; monolingual).

Materials and Procedure

*Sentence processing assessment.* Participants completed a moving window self-paced reading task (Just, Carpenter, & Woolley, 1982) at pre- and posttest. Two initial lists of Spanish sentences were created, consisting of 32 critical items and 64 fillers each (see Appendix B for examples). The critical items were eleven words long and were interpretable as either subject-first or object-first cleft sentences until the seventh, disambiguating word (Betancort, Carreiras, & Sturt, 2009; del Río et al., 2011); however, the subject-first interpretation is strongly preferred. For example:

(1) Este es el general que vigilaba al espía desde la ventana. (Subject-first)

(This is the general who watched the spy from the window.)

(2) Este es el general que vigilaba el espía desde la ventana. (Object-first)

(This is the general who the spy watched from the window.)

In Spanish, the subject-first construction is much more frequent, and the al/el manipulation results in large ambiguity effects for object-first constructions (Betancort et al., 2009). Relative to subject-first sentences, object-first constructions elicit increased first-pass and total reading times in the disambiguating region (e.g., el espía), indicating processing difficulty (Betancort et al., 2009). Moreover, this processing difficulty is associated with increased activation of neural regions implicated in cognitive control, and on average, participants incorrectly interpret more than 20% of object-first sentences, compared with only 5-10% misinterpretation in subject-first sentences (del Río et al., 2011). This suggests that participants use cognitive control to overcome a strong subject-first parsing bias in order to successfully (re)interpret object-first sentences.

Half the critical items in each list contained "al" (marking subject-first) and half contained "el" (object-first). Additionally, we swapped the "al" and "el" conditions in complementary versions of the two lists, such that subject-first sentences became object-first sentences, and vice versa. Filler sentences were seven to fourteen words long and varied in terms of syntactic structure and complexity. None of the fillers were garden-paths, but sixteen fillers in each list contained a variety of harder-to-process structures, including multiple embedded prepositional phrases, passive verbal constructions, and fronted direct objects. These items helped disguise the critical manipulation by ensuring that object-first sentences were not the only difficult items. Each sentence was followed by a True-False probe (e.g., El general vigilaba al espía (The general watched the spy)) to assess comprehension.

The majority of the critical-item probes (75%) were designed to be false, so that participants would have to successfully reanalyze the object-first sentences to respond correctly. Filler probes were balanced so that overall, each list contained half True and half False probes. True and False probes occurred with the hard fillers in the same proportions as with the rest of the fillers.

Subjects saw one list of sentences before the N-back task and a different list afterward. Sentences were presented in pseudorandom order such that critical items were never adjacent. List presentation was counterbalanced across subjects.

*N-back task.* For this task, 144 four- to eight-letter Spanish nouns and adjectives were selected from the LEXESP database via the BuscaPalabras software tool. Selection criteria were frequency between 20-30, familiarity rating between 5-7, concreteness rating between 1-3.9, and imageability rating between 3.5-7 (Davis & Perea, 2005; Sebastián-Gallés, Martí, Cuetos, & Carreiras, 2000).

The N-back task contained three blocks of 96 trials each (see Appendix C). Each block lasted about 6.5 minutes, was followed by a 1-minute break, and used a different set of Spanish words. During the task, word stimuli appeared one-by-one for 2-seconds each, with a 2-second inter-stimulus interval. Participants judged whether the current item matched or mismatched the item presented *three* trials previously. They were instructed to respond as quickly and accurately as possible, pressing one button for *targets* (i.e., 3-back matches) and another for non-matches.

In each block, 3-back targets comprised 50% of the trials. However, in the no-conflict version, all non-match trials were *non-target* words that had not appeared before, whereas in the high-conflict version, 36 out of 48 non-match trials were *lure*

items that had appeared recently, but two, four, or five trials previously. While both versions involved maintenance of attention and memory, the high-conflict version additionally required participants to override their familiarity for lure items to correctly reject them as non-matches.

  *Task analyses.* I conducted multilevel mixed-effects models with subjects and items as crossed random effects, using R's glmer function (lme4 library, Bates & Sarkar, 2007). Mixed-effects models are preferable to ANOVA because they can be more reliable (Barr, Levy, Scheepers, & Tily, 2013) and because they allow random effects of subjects and items to be considered simultaneously (Baayen, 2008). I employed linear models for RT data, but used logistic models for accuracy data because of their binomial distribution. For each analysis, I started with the full structure justified by the design; then, I conducted step-wise comparisons with simpler fixed-effects by first removing non-significant interaction terms and then removing variables without significant main-effects or interactions. The model with the lowest Akaike Information Criteria (AIC) was considered the best-fitting model and was used to calculate parameter estimates. Following the recommendation of Barr et al. (2013), I always used the full random-effects structure justified by the design unless this model a) failed to converge or b) contained random slopes that were highly correlated ($r>.9$) with the intercept or with each other. In the former case, interactions between the random slopes terms were removed before fitting the model. In the latter case, the original model's AIC was compared to the AIC when the relevant random slope was removed, and the model with the lower AIC was retained.

A parameter was considered significant if its ß-estimate was at least twice its

standard error, i.e., if the magnitude of its associated z- or t-statistic (for logistic and

linear regression, respectively) was 2 or greater (Gelman & Hill, 2007, p. 40). We

report only the results from the best fitting mixed-effect models.

*Results and Discussion*

General Analyses

There were four participants (1 no-conflict monolingual, 1 no-conflict

bilingual, and 2 high-conflict bilinguals) who initially misunderstood the task

instructions for N-back and had abnormally low accuracy on Block 1. Consequently,

Block 1 was removed for these participants, and analyses that computed gains over

the course of N-back excluded their data.

Incorrect trials were excluded from response and reading time analyses

because they may reflect different underlying cognitive processes than correct trials.

This affected 22% of N-back data and 34% of the critical subject- and object-first

items for the sentence data. Although these error rates seem high, I anticipated

relatively poor accuracy because certain items (i.e., lures on N-back and object-first

sentences) were intended to elicit errors. To reduce the effect of outliers, I replaced

responses more than 2.5 standard deviations beyond each participant's mean with the

2.5 standard-deviation threshold value. This outlier-resetting procedure affected

2.58% of correct N-back data and 2.76% of correct critical items for the sentence

processing data.[7]

N-back Performance

I examined accuracy and RT on the N-back task to determine if bilinguals

demonstrated better non-syntactic cognitive control than monolinguals and if

bilinguals and monolinguals improve differentially with practice. Because the high-

and no-conflict N-back tasks contained different trial types, I conducted mixed-effect

models separately for each conflict condition using language group, trial type, block

and their interactions as fixed effects.

*Accuracy.* Average accuracy is reported in Table 9 for both conflict

conditions. For the high-conflict N-back, the model contained significant fixed effects

of language group, block, trial type, and a block-by-trial type interaction (see Table

10). Bilinguals exhibited significantly higher accuracy than monolinguals on the

high-conflict N-back ($z$=2.43; see Figure 9), regardless of trial type or block.

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[7] Note, however, that for sentence processing data, incorrect trials were excluded after the outlier-resetting procedure so that they were included when computing subjects' residualized reading times (see Sentence Processing Results).

Table 9

*Mean (and Standard Deviation) of Accuracy for the High and No-conflict N-back Tasks*

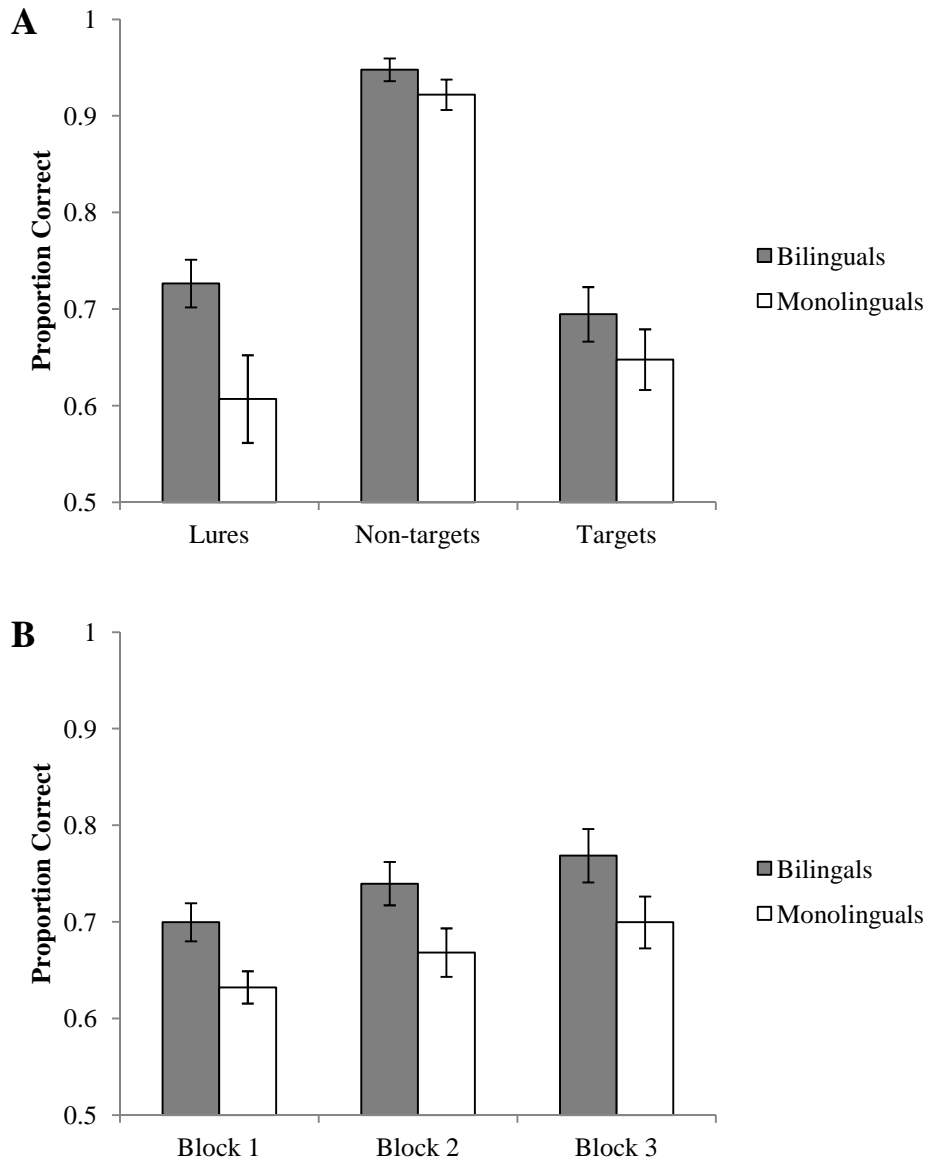| Trial type | High-conflict | | No-conflict | |
|---|---|---|---|---|
| | Bilingual | Monolingual | Bilingual | Monolingual |
| | | *Block 1* | | |
| Lures | .70 (.12) | .60 (.21) | — | — |
| Non-targets | .96 (.07) | .91 (.12) | .99 (.02) | .97 (.05) |
| Targets | .63 (.16) | .59 (.14) | .68 (.17) | .70 (.17) |
| | | *Block 2* | | |
| Lures | .72 (.18) | .60 (.24) | — | — |
| Non-targets | .94 (.09) | .91 (.13) | .98 (.03) | .97 (.06) |
| Targets | .71 (.16) | .66 (.19) | .76 (.20) | .72 (.22) |
| | | *Block 3* | | |
| Lures | .76 (.17) | .62 (.28) | — | — |
| Non-targets | .96 (.08) | .95 (.09) | .97 (.04) | .98 (.05) |
| Targets | .73 (.21) | .70 (.20) | .78 (.19) | .75 (.20) |

*Figure 9. Accuracy on the high-conflict N-back task by language group. (A) Accuracy by trial type.* There was a significant main effect of language group because bilinguals were more accurate than monolinguals. There was also a significant main effect of trial type, such that participants were more accurate on non-targets than on lures ($z=11.04$) or targets ($z=10.57$). *(B) Accuracy by block.* Participants improved significantly over the course of the task ($z=5.42$). The absence of an interaction between block and language group indicates that this improvement was equivalent for bilinguals and monolinguals.

As can be seen in Figure 9A, participants were significantly more accurate on non-targets than lures ($z=11.12$) or targets ($z=10.63$). Additionally, accuracy improved over the course of the task (see Figure 9B): participants exhibited

significantly higher accuracy at block 3 than at block 1 ($z$=3.90), although significant

improvement only occurred between the latter blocks (block 1-to-block 2: $z$=1.24;

block 2-to-block 3: $z$=3.55). Finally, although participants improved significantly on

all three trial types (lures from block 1-to-block 3: $z$=2.97; targets from block 1-to-

block 3: $z$=6.10; non-targets from block 2-to-block 3: $z$=2.38), they exhibited

significantly greater improvements on targets than lures (from block 1-to-block 2:

$z$=3.17; from block 1-to-block 3: $z$=2.97) and non-targets (from block 1-to-block 2:

$z$=2.25). Despite this, lure and target accuracy were never significantly different

(block 1: $z$=1.19; block 2: $z$=-0.60; block 3: $z$=-0.61).

Table 10

*Logistic Mixed-effects Models of Accuracy for High- and Low-Conflict N-back: Significant Model Parameters*

| Significant model parameters | Beta Estimate (SE) | z-value |
|---|---|---|
| *High-Conflict N-back* | | |
| Intercept | 1.71 (0.11) | 15.61 |
| Language group | 0.16 (0.07) | 2.43 |
| Block: Block 1 | -0.20 (0.07) | -3.01 |
| Block: Block 3 | 0.28 (0.07) | 4.09 |
| Trial type: Lure | -0.83 (0.10) | -7.97 |
| Trial type: Non-target | 1.66 (0.14) | 11.61 |
| Trial type: Target | -0.83 (0.11) | -7.44 |
| Block x Trial type: Block 1, Target | -0.15 (0.06) | -2.67 |
| Block x Trial type: Block 2, Target | 0.13 (0.05) | 2.52 |
| | | |
| *No-conflict N-back* | | |
| Intercept | 2.93 (0.13) | 22.17 |
| Trial type | 1.66 (0.11) | 14.80 |
| Block x Trial type: Block 1 | 0.18 (0.07) | 2.49 |
| Block x Trial type: Block 3 | -0.16 (0.06) | -2.56 |
| Group x Block x Trial type: Block 1 | 0.23 (0.07) | 3.24 |
| Group x Block x Trial type: Block 3 | -0.18 (0.06) | -2.75 |

Note: Significant model parameters for the best-fitting logistic mixed-effects models for N-back accuracy on the high-interference (AIC: 17285) and low-interference (AIC: 9061) tasks.

For the no-conflict condition, significant model parameters included trial type, a block-by-trial type interaction, and a three-way group, block, and trial type interaction (see Table 10). The absence of a significant main effect of group indicates that bilinguals and monolinguals had equivalent accuracy on the no-conflict task (see Table 9 and Figure 10). Participants were significantly more accurate on non-target than target trials ($z$=14.80; see Figure 10A), but they demonstrated significantly greater improvement on targets than non-targets from block 1-to-block 3 ($z$=2.87). Indeed, they became significantly more accurate from block 1-to-block 3 on target ($z$=4.81) but not non-target trials ($z$=-0.66); however, this might be attributable to near-ceiling non-target performance at block 1 (see Table 9). Finally, although

bilinguals and monolinguals' accuracy was never significantly different (block 1 targets: $z=-0.37$; block 1 non-targets: $z=1.64$; block 2 targets: $z=0.82$; block 2 non-targets: $z=0.06$; block 3 targets: $z=0.55$; block 3 non-targets: $z=-1.24$), the three-way interaction indicated that bilinguals improved more on targets and less on non-targets than monolinguals did (see Figure 10B).
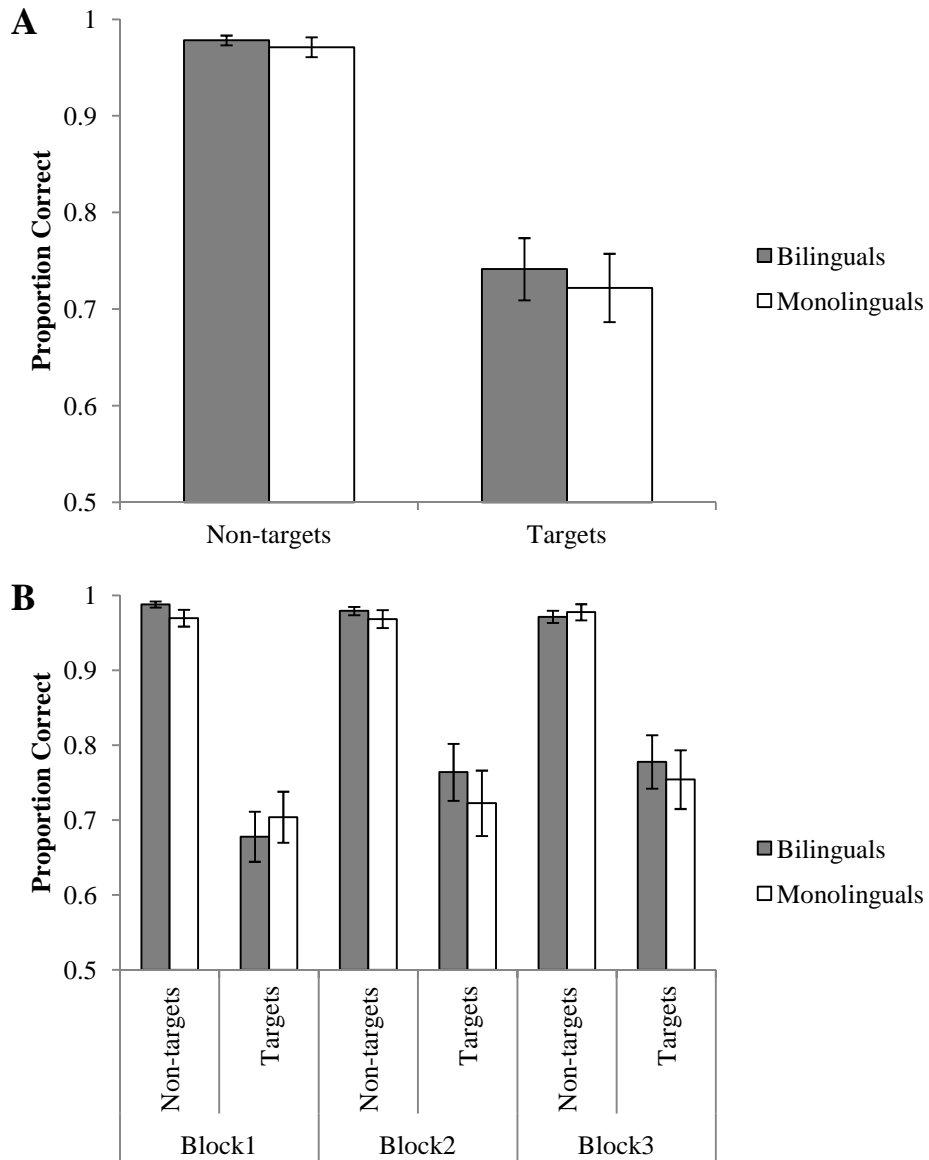
*Figure 10. Accuracy on the no-conflict N-back task by language group. (A) Accuracy by trial type.*
Participants were less accurate on targets than non-targets ($z=14.80$), but there was no main effect of
language group ($z=0.41$). *(B) Accuracy by block and trial type.* Although there was no main effect of
block or group, there was a group-by-block-by-trial type interaction, such that the difference between
bilingual and monolingual non-target accuracy was significantly smaller at block 3 than at block 1 ($z=-2.74$), whereas the difference between bilingual and monolingual target accuracy was numerically
larger at block 3 than at block 1 ($z=1.06$).

*Reaction Time (RT).* The mean RTs are reported for both conflict conditions

in Table 11. For the high-conflict N-back, significant model parameters included

block, trial type, a group-by-block interaction, a block-by-type interaction, and a

three-way group, block, and type interaction (see Table 12). Performance on lures

was significantly slower than on targets ($t$=10.74) and non-targets ($t$=9.03; see Figure 11A). Participants became significantly faster with practice from block 1-to-block 3 ($t$=7.65; see Figure 11B), although this effect was larger for lures and targets than for non-targets (see Table 11). Although there was no main effect of language group, the group-by-block interaction indicated that the difference between bilinguals and monolinguals was significantly larger at blocks 1 and 3 than at block 2 (see Figure 11). Indeed, bilinguals were significantly faster than monolinguals at block1 ($t$=-2.02), and there was a trend in this direction at block 3 ($t$=-1.88), but not at block 2 ($t$=-0.98). However, monolinguals did not improve more than bilinguals overall— rather, monolinguals became significantly faster from block 1-to-block 2 ($t$=-5.09), but not from block 2-to-block 3 ($t$=-1.61), whereas bilinguals became significantly faster from block 1-to-block 2 ($t$=-2.81) and from block 2-to-block 3 ($t$=-4.00).

Table 11

*Mean (and Standard Deviation) RTs for the High and No-conflict N-back Tasks*

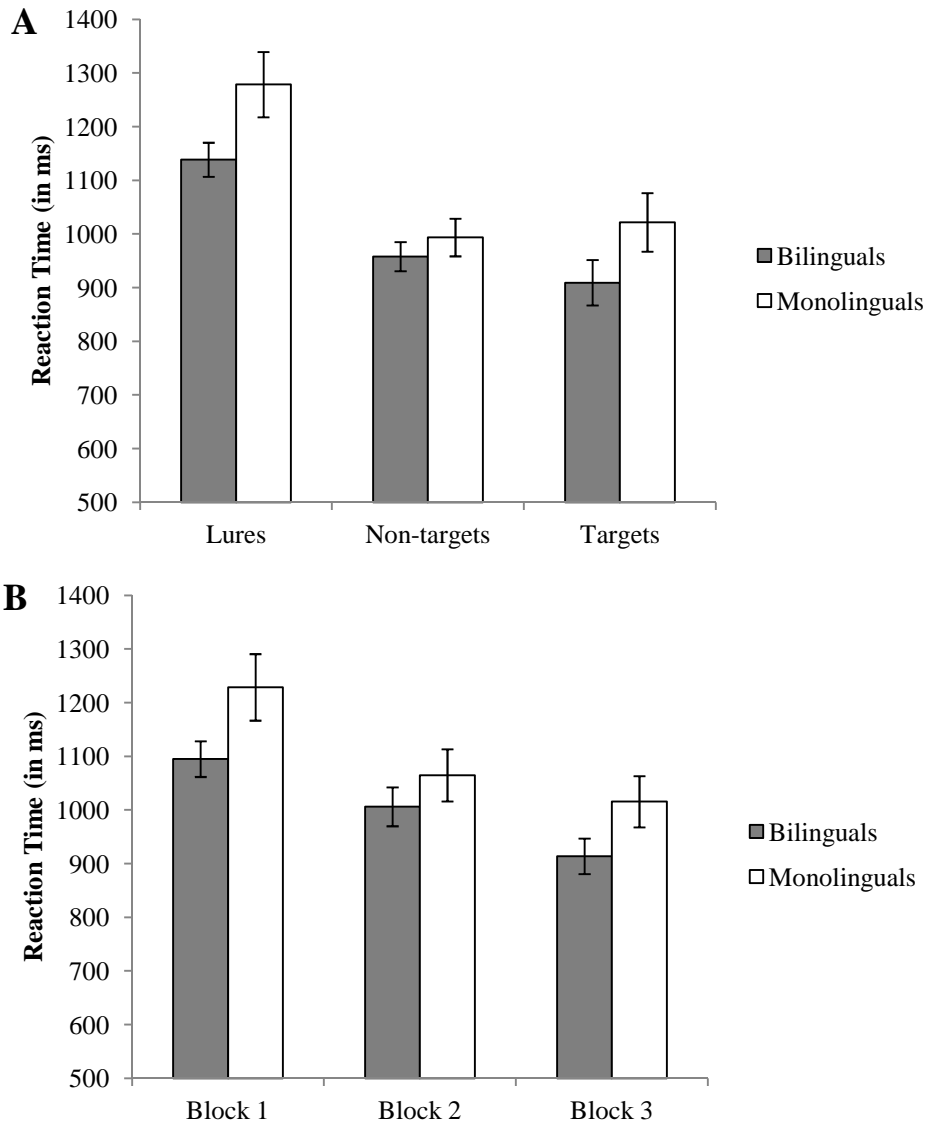| Trial type | High-conflict | | No-conflict | |
|---|---|---|---|---|
| | Bilingual | Monolingual | Bilingual | Monolingual |
| *Block 1* | | | | |
| Lures | 1206.22 (186.97) | 1409.17 (370.04) | — | — |
| Non-targets | 1005.43 (173.30) | 1053.52 (259.82) | 924.43 (490.00) | 879.30 (154.67) |
| Targets | 1047.21 (235.87) | 1170.98 (323.48) | 1148.71 (509.51) | 1129.50 (212.77) |
| *Block 2* | | | | |
| Lures | 1157.78 (233.25) | 1243.08 (316.31) | — | — |
| Non-targets | 962.20 (194.36) | 955.05 (170.46) | 884.70 (494.70) | 822.32 (144.76) |
| Targets | 919.09 (246.74) | 988.33 (270.19) | 1035.07 (540.15) | 975.76 (219.13) |
| *Block 3* | | | | |
| Lures | 1071.56 (184.45) | 1220.82 (324.09) | — | — |
| Non-targets | 901.85 (166.83) | 972.74 (207.86) | 870.35 (496.79) | 800.15 (137.86) |
| Targets | 820.14 (305.45) | 933.25 (290.49) | 996.35 (540.71) | 889.89 (239.74) |

*Figure 11. Reaction time (in ms) for bilinguals and monolinguals on the high-conflict N-back task by (A) trial type and (B) block.* (A) Overall, participants were slower on lures than on non-targets or targets. (B) Bilinguals were significantly faster than monolinguals on block 1only. However, both bilinguals and monolinguals became significantly faster over the course of the task.

Finally, the three-way interaction demonstrated that, while bilinguals were nearly always (numerically) faster than monolinguals across blocks and trial types (see Table 11), this difference was significantly larger for lures than for non-targets at block 1 ($t=2.90$) but not block 3 ($t=0.89$). Indeed, at block 1, bilinguals were significantly faster than monolinguals on lures ($t=-2.64$) but not non-targets ($t=-0.72$).

Importantly, however, the degree of bilinguals' and monolinguals' improvement from

block 1-to-block 3 did not significantly differ on either trial type (|*ts*|<1.78).

Table 12

*Linear Mixed-effects Models of RT for High- and No-conflict N-back: Significant Model Parameters*

| Significant model parameters | Beta Estimate (SE) | t-value |
|---|---|---|
| *High-Conflict N-back* | | |
| Intercept | 1052.65 (26.68) | 39.46 |
| Block: Block 1 | 91.25 (12.62) | 7.23 |
| Block: Block 3 | -74.98 (10.79) | -6.95 |
| Trial type: Lure | 156.64 (12.54) | 12.49 |
| Trial type: Non-target | -77.81 (17.18) | -4.53 |
| Trial type: Target | -78.83 (15.19) | -5.19 |
| Group x Block: Block 2 | 19.15 (8.93) | 2.15 |
| Block x Type: Block 1, Target | 36.46 (7.38) | 4.94 |
| Block x Type: Block 3, Non-target | 33.71 (9.29) | 3.63 |
| Group x Block x Type: Block 1, Lure | -17.42 (7.82) | -2.23 |
| | | |
| *No-conflict N-back* | | |
| Intercept | 945.69 (50.77) | 18.63 |
| Block: Block 1 | 77.74 (9.83) | 7.91 |
| Block: Block 2 | -17.39 (5.46) | -3.18 |
| Block: Block 3 | -60.34 (7.97) | -7.57 |
| Trial type | -83.65 (17.17) | -4.87 |
| Group x Block: Block 1 | -20.55 (9.25) | -2.22 |
| Group x Block: Block 3 | 17.83 (7.69) | 2.32 |
| Block x Type: Block 1 | -44.11 (5.26) | -8.39 |
| Block x Type: Block 2 | 10.43 (4.25) | 2.45 |
| Block x Type: Block 3 | 33.68 (4.49) | 7.51 |
| Group x Block x Type: Block 1 | 10.08 (4.09) | 2.46 |
| Group x Block x Type: Block 3 | -10.37 (3.99) | -2.60 |

*Note*. Significant model parameters for the best-fitting linear mixed-effects models for N-back RT on the high-conflict (AIC=172518) and no-conflict (AIC=181950) tasks.


The model for the no-conflict condition included significant effects of block,

trial type, a group-by-block interaction, a block-by-type interaction, and the three-

way group, block, and type interaction (see Table 12). As reported in Table 11, RTs

were significantly slower on targets than non-targets (*t*=4.87; see Figure 12).

Participants became significantly faster from block 1-to-block 2 (*t*=-7.14) and block

2-to-block 3 ($t=-4.53$) and improved on both trial types (targets: $t=-11.09$; non-targets: $t=-3.24$); however, they improved significantly more on targets than on non-targets (block 1-to-block 2: $t=-6.42$; block 2-to-block 3: $t=-3.35$). The language groups improved at different rates, with monolinguals improving more than bilinguals from block 1-to-block 3 ($t=-2.38$), but this effect was only significant for target trials ($t=-3.21$). Importantly, however, both groups improved significantly during the task (monolinguals: $t=-7.38$; bilinguals: $t=-4.35$), and monolinguals were never significantly faster than bilinguals on targets (block 1: $t=.07$; block 2: $t=-.50$; block 3: $t=-.96$) or non-targets (block 1: $t=-.33$; block 2: $t=-.59$; block 3: $t=-.69$).
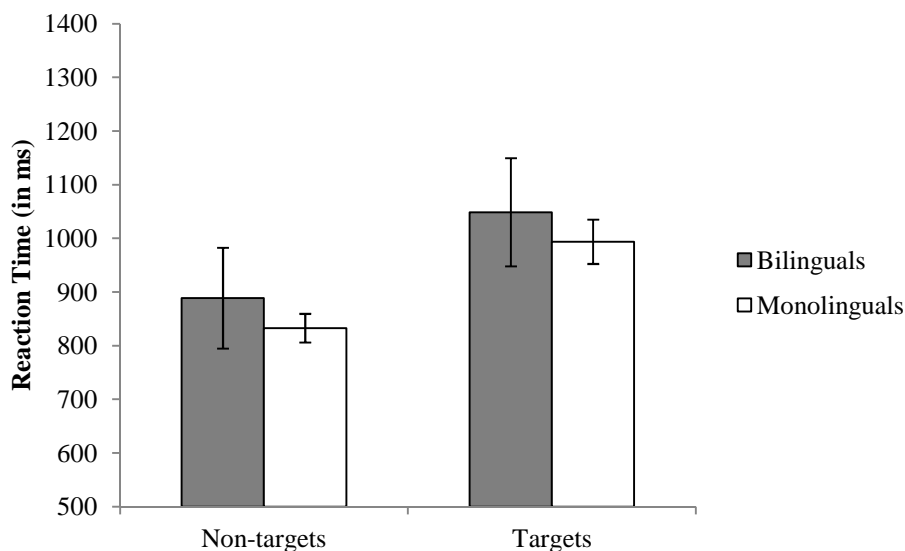


*Figure 12. Reaction time (in ms) on the no-conflict N-back task by trial type.* Bilinguals and monolinguals exhibited equivalent RTs in the no-conflict condition ($t=.53$). Participants were slower on targets than on non-targets ($t=4.87$).

*Discussion of N-back performance.* Bilinguals were more accurate and faster than monolinguals on a high-conflict N-back task, extending the bilingual advantage in cognitive control to a recognition-memory paradigm. As predicted, the effect of bilingualism emerged across both conflict (lure) and non-conflict (target and non-

target) trials, suggesting that it reflects superior conflict monitoring—under conditions with high monitoring demands, bilinguals are more accurate than monolinguals at recognition memory, which may indicate that bilinguals are better at detecting conflicts and flexibly employing cognitive control.

As expected, participants were less accurate and slower on lures than non-targets, indicating increased difficulty of lure trials. This difficulty is presumably due to the need to resolve conflict between the familiarity of the lure and the correct serial-position information. Interestingly, however, target accuracy was equivalent to lure accuracy, whereas target RTs were faster than lure RTs. This pattern suggests that serial-position may not be well-encoded on the high-conflict N-back, leading to substantial error rates (33%) for both lures and targets. However, when serial-position is correctly encoded, participants identify targets more quickly than lures. The increased difficulty of lures relative to non-targets and targets suggests that only lures require conflict resolution. Considered alongside evidence that bilinguals outperformed monolinguals regardless of trial type, this reinforces the idea that the bilingual advantage is not specific to conflict trials.

One of the aims of Experiment 4 was to determine whether bilinguals and monolinguals improve differentially with practice. I found that, independent of language group, participants improved performance on both accuracy and RT during a high-conflict N-back task; moreover, bilinguals continued to achieve significantly higher accuracy (and numerically faster RTs) than monolinguals throughout the 20-minute task. Thus, the bilingual advantage may be more robust to practice effects than previously supposed.

Unlike in the high-conflict N-back, bilinguals and monolinguals exhibited equivalent accuracy and RTs on the no-conflict N-back. This finding was consistent with the hypothesis that bilinguals should not perform better than monolinguals on tasks without information-processing conflict. Crucially, the no-conflict N-back was identical to the high-conflict N-back except for the inclusion of lures, indicating that the bilingual advantage cannot be explained by better attention or memory abilities alone; rather, the presence of conflict is necessary to elicit the bilingual advantage.

Overall, the N-back results show that relative to monolinguals, bilinguals enjoy an advantage in cognitive control, but not in basic attention or memory abilities. This advantage is robust to practice if the task is sufficiently demanding such that bilinguals and monolinguals have equal opportunity to improve. Finally, consistent with the conflict monitoring account, I show a bilingual advantage across conflict and non-conflict trials.

Sentence Processing Performance

I examined sentence comprehension accuracy and reading times to test whether the bilingual advantage extends to sentence processing and whether brief cognitive control practice (i.e., the conflict condition of the intervening 3-back task) mediated the relationship between language experience and sentence processing. Because ambiguity occurred unpredictably in the sentence processing task, all of the sentences should require conflict monitoring; therefore, I included fillers in addition to subject- and object-first sentences in our analyses of comprehension accuracy. However, fillers were omitted from reading time analyses because they contained a

fundamentally different structure than critical sentences, so reading times would not reflect comparable syntactic processing.

*Sentence Comprehension.* Mean sentence comprehension accuracy is reported in Table 13. Significant model parameters included language group (bilingual/monolingual), block (pre/post), sentence type (subject-first/object-first/filler), and a block-by-sentence type interaction (see Table 14). The best-fitting model dropped the effect of N-back conflict condition, indicating that N-back version did not influence sentence comprehension accuracy.

Table 13

*Mean (and Standard Deviation) of Sentence Comprehension Accuracy for Bilinguals and Monolinguals for Each Sentence Type at Pretest and Posttest*

| Sentence type | Pretest | | Posttest | |
|---|---|---|---|---|
| | Bilingual | Monolingual | Bilingual | Monolingual |
| Subject-first | .90 (.12) | .86 (.13) | .89 (.10) | .87 (.13) |
| Object-first | .42 (.31) | .40 (.30) | .51 (.37) | .47 (.32) |
| Fillers | .92 (.05) | .90 (.06) | .93 (.05) | .89 (.07) |

Bilinguals exhibited significantly higher sentence comprehension accuracy than monolinguals ($z=3.20$; see Table 13) across sentence types and assessments. Participants were less accurate on object-first than subject-first ($z=-13.90$) or filler sentences ($z=-14.72$) and less accurate on subject-first than filler sentences ($z=-3.16$). Comprehension accuracy was higher at posttest than pretest ($z=3.04$), but participants only made significant gains on object-first sentences ($z=5.68$). Still, object-first accuracy remained significantly lower than subject-first ($z=-11.79$) and filler sentences ($z=-13.24$) at posttest.

Table 14

*Logistic Mixed-effects Models of Accuracy on Sentence Comprehension Probes: Significant Model Parameters*

| Significant model parameters | Beta Estimate (SE) | z-value |
|---|---|---|
| Intercept | 1.64 (0.12) | 13.63 |
| Language group | 0.20 (0.06) | 3.20 |
| Block | 0.10 (0.03) | 3.04 |
| Sentence type: subject-first | 0.72 (0.09) | 7.73 |
| Sentence type: object-first | -1.95 (0.13) | -15.56 |
| Sentence type: filler | 1.23 (0.11) | 11.24 |
| Block x Sentence type: object-first | 0.18 (0.04) | 4.94 |
| Block x Sentence type: filler | -0.11 (0.03) | -3.13 |

*Note.* Significant model parameters for the best-fitting logistic mixed-effects model for sentence comprehension accuracy (AIC=13335).

*Reading Times.* Only critical items (object- and subject-first sentences) were analyzed, and the final word of each sentence was excluded to prevent wrap-up effects from obscuring the effects of interest or creating spurious effects. As detailed above (see General Analyses), I first reset each subject's outliers to their 2.5 standard-deviation threshold. I then computed each subject's residual reading times by regressing length and reading times in each region and calculating deviations from the expected reading time. This procedure factors out the effects of word length and individual differences on reading duration (Ferreira & Clifton, 1986; Trueswell, Tanenhaus & Garnsey, 1994). Incorrect trials were excluded prior to statistical analyses.

Residualized reading times were analyzed separately for each word in the sentence using linear mixed-effects models with fixed effects for group (monolingual/bilingual), block (pre/posttest), conflict (high/low), and trial type (subject/object-first), and their interactions. Since the subject- and object-first items were identical up to word 7 (el/al), which was the critical disambiguating region, the

primary regions of interest were words 7-10. However, analyses were conducted on all regions to verify that there were no unanticipated effects.

Table 15

*Linear Mixed-effects Models of Residual Sentence Reading Times by Region:*
*Significant Model Parameters*

| Significant model parameters | Beta Estimate (SE) | t-value |
|---|---|---|
| *Word 1 (Este)* | | |
| Block | -23.90 (4.25) | -5.63 |
| Group x Block | -9.49 (3.75) | -2.53 |
| | | |
| *Word 2 (es)* | | |
| Block | -26.38 (4.23) | -6.24 |
| Group x Block | -7.76 (3.79) | -2.05 |
| | | |
| *Word 3 (el)* | | |
| Block | -25.23 (3.61) | -6.98 |
| | | |
| *Word 4 (general)* | | |
| Block | -60.01 (7.67) | -7.83 |
| | | |
| *Word 5 (que)* | | |
| Block | -36.07 (4.73) | -7.63 |
| | | |
| *Word 6 (vigilaba)* | | |
| Block | -63.94 (8.33) | -7.68 |
| | | |
| *Word 7 (el/al)* | | |
| Block | -36.00 (6.30) | -5.71 |
| | | |
| *Word 8 (espía)* | | |
| Block | -81.82 (10.08) | -8.12 |
| Type | 43.16 (8.81) | 4.90 |
| | | |
| *Word 9 (desde)* | | |
| Block | -34.86 (5.11) | -6.82 |
| Type | 36.39 (4.80) | 7.58 |
| | | |
| *Word 10 (la…)* | | |
| Block | -26.66 (4.17) | -6.39 |
| Type | 19.70 (3.87) | 5.09 |
| Group x Block x Interference x Type | 10.55 (4.19) | 2.52 |

*Note*. Significant model parameters for the best-fitting linear mixed-effects models for residual sentence reading times for each word in the sentence: Word 1 (AIC=62130); Word 2 (AIC=60408); Word 3 (AIC=60524); Word 4 (AIC=65516); Word 5 (AIC=62627); Word 6 (AIC=66656); Word 7 (AIC=65008); Word 8 (AIC=69625); Word 9 (AIC=66669); Word 10 (AIC=63644).

Table 15 reports significant model parameters in each sentence region. The

canonical garden-path effect is evidenced by significant effects of trial type in words

8, 9, and 10 ($|ts|>4.89$), reflecting increased reading times for object-first relative to subject-first sentences (see Table 16 for mean reading times). As expected, there was no effect of trial type prior to word 7. The absence of group x trial type interactions in the early disambiguating regions (words 7-9) suggests that the garden-path effect was equivalent in bilinguals and monolinguals. This is somewhat qualified, however, by a significant group x block x conflict x trial type interaction at word 10, which emerged because among bilinguals, both the high- and no-conflict groups demonstrated significant cross-assessment reading time improvements on object- and subject-first sentences ($|ts|>2.15$), but among monolinguals, the high-conflict group improved significantly on object-first ($t=-4.33$) but not subject-first sentences ($t=-1.87$), whereas the no-conflict group improved significantly on subject- ($t=-4.06$) but not object-first sentences ($t=.02$). This resulted in no-conflict monolinguals having significantly slower residual reading times on object-first sentences at posttest ($M=29.67$, $SD=292.44$) than high-conflict monolinguals ($M=-25.10$, $SD=198.63$; $t=2.53$) or no-conflict bilinguals ($M=-16.03$, $SD = 222.22$; $t=2.08$).

Table 16

*Mean Outlier-reset and Residual Reading Times for the Disambiguating Regions of the Subject- and Object-cleft Items, Pooled across Pretest and Posttest and across Monolinguals and Bilinguals*

| Sentence Type | Word7 | Word8 | Word9 | Word10 |
|---|---|---|---|---|
| | *... el/al* | *espía* | *desde* | *la ...* |
| **Mean Outlier-Reset Reading Times** | | | | |
| Subject | 480.77 | 664.64 | 481.70 | 412.71 |
| Object | 517.32 | 841.91 | 580.66 | 474.92 |
| *Difference* | 36.55 | 177.27 | 98.96 | 62.21 |
| **Mean Residual Reading Times** | | | | |
| Subject | 0.72 | -32.55 | -28.88 | -16.17 |
| Object | -5.73 | 46.75 | 39.25 | 23.53 |
| *Difference* | -5.01 | 79.30* | 68.13* | 39.70* |

*Note.* *$|t|$>2. Negative residual values reflect faster reading times than predicted given word length; positive residuals reflect slower reading times than predicted given word length.

Participants also exhibited a reliable practice effect: they were faster at posttest than pretest at every word ($|t$s$|$>5.62; see Table 15). There were also significant interactions of group and block at words 1 and 2. At word 1, both bilinguals ($t$=-7.01) and monolinguals ($t$=-3.01) demonstrated significant decreases in their reading times from pretest (bilinguals: *M*=33.91, *SD*=222.66; monolinguals: *M*=20.99, *SD*=190.94) to posttest (bilinguals: *M*=-34.10, *SD*=137.96; monolinguals: *M*=-11.64; *SD*=204.73), but bilinguals improved significantly more than monolinguals ($t$=2.81). Similarly, at word 2, both bilinguals ($t$=-6.24) and monolinguals ($t$=-3.18) improved significantly from pretest (bilinguals: *M*=32.53, *SD*=158.58; monolinguals: *M*=19.53, *SD*=183.26) to posttest (bilinguals: *M*=-37.37, *SD*=117.56; monolinguals: *M*=-20.50, *SD*=177.09), but bilinguals improved to a greater extent ($t$=2.05).

*Discussion of sentence processing performance.* I found a small yet reliable effect of bilingualism on sentence comprehension accuracy, such that bilinguals had

better reading comprehension than monolinguals irrespective of sentence type or assessment. To my knowledge, this is the first demonstration that the bilingual advantage extends to parsing tasks involving occasional garden-path sentences. Interestingly, this bilingual advantage was not specific to temporarily ambiguous, object-first sentences, suggesting that the mere presence of occasional conflict and thus the demand to monitor for conflict is driving the bilingual sentence comprehension advantage. The advantage persisted across both assessments, demonstrating that the bilingual advantage is robust to practice effects on sufficiently challenging tasks. However, bilinguals did not differ from monolinguals in their reading times, suggesting that bilinguals' cognitive control advantage may only impact late-stage revision processes (see General Discussion).

Unsurprisingly, the sentences induced the expected effect of ambiguity, as participants were slower in the disambiguating regions of and less accurate on comprehension probes for object- than subject-first sentences. However, the magnitude of the ambiguity effect was not differentially impacted by practice on the high- versus the low-conflict version of N-back as I had expected. Instead, the ambiguity effect was largely stable across language and conflict groups, although overall it was reduced (but not eliminated) for sentence comprehension at posttest, due to selective gains on object-first sentences. Thus, regardless of the type of intervening N-back task (high- or no-conflict), all participants improve at processing syntactic ambiguity merely through repeated exposure to similar materials. Such effects of practice on syntactic ambiguity resolution are consistent with prior

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literature (Long & Prat, 2008; Wells, Christiansen, Race, Acheson, & MacDonald, 2009).

It is worth noting, however, that the N-back conflict condition *was* related to the ambiguity effect in reading times for word 10: in this region, bilinguals exhibited cross-assessment decreases in reading times on both sentence types regardless of N-back conflict condition, whereas monolinguals improved selectively on object-first sentences following the high-conflict N-back, but selectively on subject-first sentences following the no-conflict N-back. However, this effect was rather late in the disambiguating region; indeed, word 10 occurred three words after the initial disambiguating word. Thus, the interaction may be more attributable to wrap-up effects rather than to differential improvement in ambiguity resolution per se.

*General Discussion: Experiment 4*

I observed a bilingual advantage across two tasks sharing a common cognitive control component, namely, a high-conflict N-back task and sentence processing involving syntactic ambiguity resolution. The observation of a bilingual advantage on both tasks is one of the first demonstrations that bilingualism bolsters performance reliably across tasks relying on common cognitive control resources.

The bilingual advantage manifested in a similar pattern across both tasks, emerging on both conflict trials and non-conflict trials. Because the bilingual advantage consistently extended beyond those trials requiring conflict resolution, the current results support the conflict monitoring theory (Costa et al., 2009; Hilchey & Klein, 2011), which characterizes the bilingual advantage as a superior ability to

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detect conflict and flexibly adjust recruitment of cognitive control resources. According to this account, the bilingual advantage emerges because the occasional presence of conflict heightens monitoring demands, thereby increasing the readiness of cognitive control functions to deploy. This state of heightened readiness leads to improved performance on both conflict and non-conflict trials. In essence, under high demands, the monitor must be prepared either deploying or reserving cognitive control resources on a moment-to-moment basis. Bilinguals seem to be more adept than monolinguals at flexibly engaging cognitive control.

Finally, I found that the bilingual advantage emerged across tasks and was sustained throughout cognitive control practice, suggesting that it is both consistent and robust. It is consistent in that within the same subject groups, bilinguals outperformed monolinguals on two ostensibly different tasks (e.g., recognition memory and sentence reading) that nevertheless tap common cognitive control mechanisms, and it is robust because monolinguals did not 'catch up' to bilingual performance over the course of an experiment, when tested on sufficiently challenging tasks.

### N-back Performance

Analyses of N-back performance indicated that bilinguals were faster and more accurate than monolinguals, but only on the high-conflict version, which required cognitive control to override a misleading familiarity bias on lure trials. No such advantage emerged on the no-conflict N-back task, which involved the maintenance of attention and memory but which contained no lure trials and thus did not require cognitive control. This divergence across the two versions of N-back is

critical; if an advantage had emerged on the no-conflict task, then the results would have suggested that bilinguals had merely paid better attention than monolinguals, as cognitive control should not deploy in the total absence of conflict. Instead, I found a bilingual advantage only on N-back involving frequent conflict, confirming that the advantage reflects improved cognitive control, rather than better attention or memory. Said another way, bilinguals do not appear to enjoy an advantage in the mnemonic aspects of working memory, when information must be maintained for ongoing use in the absence of interfering representations; rather, their advantage emerges only when the demands for non-mnemonic control processes are relatively high, namely when conflict must be detected and resolved throughout a particular task context.

One alternative explanation for the advantage's disappearance on the no-conflict N-back task is that without conflict, the task became too easy, obscuring any group differences in recognition-memory. However, I find this unlikely given the observed pattern of results. Correctly identifying target items evidently taxed attention and memory resources: participants were significantly less accurate and slower on targets than on non-targets, correctly responding on only 73% of targets. Moreover, participants became significantly more accurate and faster on targets with practice, indicating sufficient room for improvement. These results suggest that bilinguals and monolinguals performed equivalently on the no-conflict N-back task not because they were at ceiling, but because they had equivalent attention and memory abilities.

In contrast to previous studies, which may have been susceptible to task-ceiling effects, I showed that both bilinguals and monolinguals improve markedly

during practice on a cognitive control task. Indeed, regardless of language group, participants in the high-conflict condition increased their N-back accuracy by nearly 7%. In reaction time, a group-by-block interaction suggested that bilinguals and monolinguals improved at different rates; however, bilinguals still became significantly faster with practice, and monolinguals never achieved bilingual-levels of performance. This novel finding is important because it suggests that despite bilinguals already possessing better conflict monitoring and cognitive control abilities, they are nevertheless able to benefit from further practice. Moreover, it shows that a mere 20 minutes of cognitive control practice by monolinguals does not produce cognitive control benefits comparable to those endowed by a lifetime of bilingual experience.

Sentence Processing Performance

Bilinguals exhibited a small, non-specific advantage over monolinguals in offline sentence processing throughout the study, as evidenced by their higher accuracy on comprehension probes following all sentence types (object-first, subject-first, and filler). However, bilinguals' online sentence processing was not superior to monolinguals'. A bilingual advantage in reading comprehension but not real-time parsing suggests that the observed advantage may impact late-stage semantic-integration processes. However, it is worth noting that prior studies have observed slower lexical access in bilinguals relative to monolinguals (for review, see Bialystok et al., 2009), either because of reduced lexical frequency (Gollan, Montoya, Cera, & Sandoval, 2008) or because of increased competition for word selection due to interference from the irrelevant language (Sandoval, Gollan, Ferreira, & Salmon,

2010). It is therefore likely that bilinguals suffer a measurable *disadvantage* at the early stages of sentence processing (e.g., lexical retrieval), but their increased cognitive control enables them to compensate in comprehension.

Crucially, bilinguals' sentence comprehension advantage was not selective for sentences requiring ambiguity resolution. These results parallel the findings from the N-back task, further corroborating the idea that bilinguals are better at conflict detection and the flexible recruitment of cognitive control. Again, however, I would not expect a global bilingual advantage in sentence comprehension in the complete absence of temporarily ambiguous sentences; indeed, the relatively low proportion of garden-paths in the sentence processing task may account for the small magnitude of the bilingual advantage in sentence comprehension (and lack thereof in real-time processing). Specifically, the asymmetrical distribution of conflict (17%) and non-conflict trials (83%) in our sentence processing task may reduce monitoring demands, because switching between conflict and non-conflict trials is relatively infrequent. The conflict monitoring theory predicts that the bilingual advantage should be largest when the need to monitor for conflict is high, and prior studies (Costa et al., 2009) have shown that the bilingual advantage disappears on the Flanker task when a high-proportion (92%) of trials are the same type (either conflict or non-conflict). Thus, bilinguals' sentence comprehension advantage may have been relatively small in the present study because conflict monitoring demands were relatively low. Future studies should determine whether this advantage could be increased with a higher degree of switching between garden-path and unambiguous sentences.

Caveats and Limitations

The extent to which the differences I observed between bilinguals' and monolinguals' cognitive control abilities can be attributed to bilingual language experience is limited by the extent to which the two language groups are comparable in all factors other than language experience. All our subjects were healthy, young adults recruited from the same institution, and for the subset of individuals who provided SES data, there were no significant differences across the language groups. Because we were not able to collect SES data from all of our subjects, we cannot entirely rule out the possibility that, overall, bilinguals and monolinguals came from different socioeconomic backgrounds. However, this seems unlikely, since we have no reason to believe that the participants who provided SES data were not representative of the groups as a whole.

Another possible difference between our bilingual and monolingual groups is immigrant status, as a greater proportion of the bilingual participants (high-conflict: 93.8%; no-conflict: 88.9%) than monolingual participants (high-conflict: 57.7%; no-conflict: 48%) were originally from Spain. Thus, more monolinguals than bilinguals were immigrants (since in Barcelona, the local population is largely bilingual). This would principally be a concern if the two groups differed in terms of education level—when immigrant status has been suggested as an alternative explanation for the bilingual advantage, the bilingual group in question contained more Canadian immigrants, who tend to have more education than native Canadians (Morton & Harper, 2007, 2009). This artifact of immigrant status seems unlikely in the present study, given that all participants were students at the University of Barcelona,

primarily at the undergraduate level. Moreover, if anything, these bilinguals had slightly less, not more, education than our monolinguals, as monolinguals were more likely to be graduate students. Thus, the most parsimonious account of the evidence for a bilingual advantage in cognitive control is that bilingualism, rather than differences in immigrant status, is responsible for the increase in cognitive control abilities.

The findings of Experiment 4 directly contrast with recent studies that have failed to find a bilingual advantage across a variety of different executive function tasks (Hilchey & Klein, 2011; Paap & Greenberg, 2013). An explanation of such discrepancies is warranted: why did the advantage emerge consistently across executive function tasks in the present experiment, but not in Paap and Greenberg's (2013), which was explicitly designed to examine the cross-task consistency of the bilingual advantage? I believe that although the tasks in Paap and Greenberg's study (Simon, Flanker, Antisaccade, Ravens Progressive Matrices, and Color-Shape Switching) can all be broadly classified as executive function tasks, they rely on different aspects of executive control and are not actually assessing the same abilities. For instance, the Flanker task involves ignoring irrelevant-information whereas color-shape switching requires cognitive flexibility. Additionally, many of these tasks are susceptible to ceiling effects, making it difficult to observe individual differences on these tasks in young adults, who are at their executive function peak. Indeed, previous studies have observed a reduction in color-shape switching costs (Gold et al., 2013) and in the Simon effect (Bialystok et al., 2004) for bilinguals relative to monolinguals in older but not younger adult populations, suggesting that although bilingualism

improves performance on these tasks, it is difficult to detect this advantage in young adults.

In contrast, N-back with lures and syntactic ambiguity resolution are hypothesized to recruit shared cognitive control resources (Novick et al., 2005), a hypothesis which is well-supported by their similar neural and behavioral profiles (January et al., 2009; Novick et al., 2009, 2013). Moreover, these tasks are difficult even for healthy young adults, making it easier to observe group differences in cognitive control. Indeed, in Experiment 4, the bilingual advantage was primarily reflected in accuracy: bilinguals were more accurate than monolinguals on the N-back task and on sentence comprehension probes. Such a result may be harder to obtain on tasks like Simon and Flanker, where accuracy is close to ceiling (Paap & Greenberg, 2013). Indeed, ceiling effects may have contributed to the apparent lack of group differences on the Stroop task in Experiment 2.

Concluding Remarks

In conclusion, bilingualism apparently acts as a form of cognitive control training, bestowing measurable advantages in conflict monitoring, the ability to detect unpredictable conflict and flexibly adjust recruitment of cognitive control resources. I demonstrate that this advantage applies not only to recognition-memory under high-monitoring demands, but also to sentence processing involving occasional syntactic ambiguity resolution, suggesting that conflict monitoring operates across syntactic and non-syntactic domains. Moreover, this system continues to be amenable to improvement, as both bilinguals and monolinguals made substantial gains with practice. Taken together, these results support the theory that bilinguals possess a

more-developed flexible cognitive control system. This increased flexibility is domain-general, underlying bilinguals' heightened detection and resolution of information-conflict during parsing and interpretation (i.e., when syntactic ambiguity is present) and within recognition memory.

# Chapter 6: General Discussion

The present dissertation, in conjunction with previous research, supports the existence of a bilingual advantage in conflict monitoring. Experiment 1 appeared to confirm that conflict adaptation effects reflect online adjustments in the recruitment of domain-general cognitive control resources. Experiments 2 and 3 demonstrated that bilinguals were less affected than monolinguals by sequential effects: specifically, whereas monolinguals had lower accuracy following congruent trials than incongruent trials, suggesting difficulty in detecting initial conflicts, bilinguals exhibited equally high accuracy after both congruent and incongruent trials. In conjunction with the finding that bilinguals exhibit increased recruitment of neural regions involved in language-switching, attention orienting, and control during conflict detection, these results suggest that bilinguals engage a broader network of control to enable better conflict detection. Finally, Experiment 4 demonstrated that the bilingual advantage transfers to linguistic tasks and can emerge consistently across different executive function tasks tapping a common conflict monitoring system. Importantly, these results replicate the finding of a 'global' advantage across conflict and non-conflict trial types, while showing that it does not occur in the absence of conflict, further supporting the notion that bilingualism improves conflict monitoring.

However, we are only beginning to understand the exact nature and extent of the bilingual advantage. If the bilingual advantage is best characterized as superior

conflict monitoring, then the mechanisms that would strengthen conflict monitoring in bilinguals need to be delineated. As discussed in Chapters 1 and 3, recent neuroimaging evidence suggests that the processes underlying language-switching may be instrumental to the bilingual advantage in cognitive control. Indeed, language-switching during a picture-naming task and conflict trials on a Flanker task activate overlapping areas of the anterior cingulate cortex (Abutalebi et al., 2012), a region that has been linked to conflict monitoring processes, specifically, detecting conflict and subsequently adjusting control (Botvinick et al., 1999, 2001, 2004; Kerns et al., 2004). Because language-switching engages the same resources as conflict monitoring, it is plausible that the processing demands associated with switching languages confer a conflict monitoring advantage to bilinguals who must frequently shift between their two languages. Indeed, the present study is consistent with this interpretation, given that bilinguals recruited regions involved in language-switching (e.g., the left caudate) to a greater extent than monolinguals during conflict detection.

If language-switching is indeed responsible for the bilingual advantage, one might expect that those bilinguals who switch languages frequently enjoy larger advantages than those who only rarely switch. In other words, the conflict monitoring advantage may only emerge in certain bilingual communities. Bilinguals in code-switching environments may have an especial need to monitor for conflict, because they are charged with detecting unpredictable language switches (Valdés Kroff, Dussias, Gerfen, & Perrotti, submitted), requiring flexible deactivation and reactivation of lexical items. Unlike bilinguals in single-language environments, code-switchers may maintain activation of both languages to facilitate switching,

instead of globally inhibiting the language not currently in-use (Green, 2011). If code-switching imposes especially strong conflict monitoring demands, this may help explain some of the inconsistencies in the bilingual advantage literature. Future studies should address this possibility by examining whether code-switching comprehension requires conflict monitoring.

# Appendices

**Demographic Information**

Participant ID

Please enter your current age in years.

If you are in school, please list your major(s).

Please indicate your gender.
- Male
- Female

Please enter your race/ethnicity. Check all that apply.
- American Indian or Alaskan Native
- Asian
- Black or African American
- Hispanic
- Native Hawaiian or Other Pacific Islander
- White (non-Hispanic)
- Other

What is the highest level of education you have completed? (Note: If you are currently in college, but do not yet have a Bachelor's, you should choose 'Some college').
- Less than high school
- Some high school
- High-school diploma or GED
- Trade school
- Some college
- Bachelor's degree
- Some graduate school
- Master's or Professional Degree
- Ph.D., J.D., M.D. or other Doctorate

What is the highest level of education completed by your mother or female guardian?

- Less than high school
- Some high school
- High school diploma or GED
- Trade School
- Some college
- Bachelor's degree
- Some Graduate School
- Masters or Professional Degree
- Ph.D., J.D., M.D., or other Doctorate
- I was not raised by my mother or female guardian.

What is the highest level of education completed by your father or male guardian?

- Less than high school
- Some high school
- High school diploma or GED
- Trade School
- Some college
- Bachelor's degree
- Some Graduate School
- Masters or Professional Degree
- Ph.D., J.D., M.D., or other Doctorate
- I was not raised by my father or male guardian.

How many people lived in the household in which you were raised?

- 2
- 3
- 4
- 5
- 6
- 7
- 8+

Please estimate the total household income of the household in which you were raised.

- ○ $0-15,000
- ○ $15,000-25,000
- ○ $25,000-35,000
- ○ $35,000-45,000
- ○ $45,000-55,000
- ○ $55,000-65,000
- ○ $65,000-75,000
- ○ $75,000-85,000
- ○ $85,000-100,000
- ○ $100,000-150,000
- ○ $150,000-250,000
- ○ $250,000+

Please estimate the socioeconomic status of your parent(s) or guardian(s).

- ○ Underclass (poor, unemployed)
- ○ Working Poor
- ○ Working Class
- ○ Middle Class
- ○ Upper Middle Class
- ○ Upper Class

## CABB

What is your native (i.e.- your first) language?

What is your preferred language (i.e.- the language you feel most comfortable speaking)?

Please indicate your country of origin/birth:

Please indicate your country of residence:

If your country of origin and residence are not the same, at what age did you move to your country of residence?

If you have lived in multiple countries, please list them and the amount of time you spent in each one:

What languages do you speak fluently/proficiently? Please list in order from most proficient to least proficient.

The following questions ask what proportion of the time you spoke English versus Spanish at different times in your life and in different settings. If you used only 1 language, you should use the endpoints of scale. The selection "Almost Always" should mean you used that language more than 80% of the time, the selection "Mostly" should mean that you used that language between 60 and 80% of the time, and the selection "Equivalently" should mean that you used each language between 40 and 60% of the time. Please answer only in regards to English and Spanish. If your primary language was something other than English or Spanish, please let the experimenter know.

Prior to school, how often did you hear each language?

|  | Always English | Almost Always English | Mostly English | Equivalently English/ Spanish | Mostly Spanish | Almost Always Spanish | Always Spanish |
|---|---|---|---|---|---|---|---|
| At home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

During elementary school, what language did you speak the most?

|  | Always English | Almost Always English | Mostly English | Equivalently English/ Spanish | Mostly Spanish | Almost Always Spanish | Always Spanish |
|---|---|---|---|---|---|---|---|
| At home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| At school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| With friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

During middle school, what language did you speak the most?

|  | Always English | Almost Always English | Mostly English | Equivalently English/ Spanish | Mostly Spanish | Almost Always Spanish | Always Spanish |
|---|---|---|---|---|---|---|---|
| At home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| At school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| With friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

During high school, what language did you speak the most?

| | Always English | Almost Always English | Mostly English | Equivalently English/ Spanish | Mostly Spanish | Almost Always Spanish | Always Spanish |
|---|---|---|---|---|---|---|---|
| At home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| At school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| With friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

During college and as an adult, what language do you speak the most?

| | Always English | Almost Always English | Mostly English | Equivalently English/ Spanish | Mostly Spanish | Almost Always Spanish | Always Spanish |
|---|---|---|---|---|---|---|---|
| At home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| At school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| With friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Please indicate your proficiency in speaking for all the languages that you know.

| | Not at all proficient | Somewhat proficient | Moderately proficient | Quite proficient | Fluent |
|---|---|---|---|---|---|
| English | ○ | ○ | ○ | ○ | ○ |
| Spanish | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |

Please indicate your proficiency in writing for all the languages that you know.

| | Not at all proficient | Somewhat proficient | Moderately proficient | Quite proficient | Fluent |
|---|---|---|---|---|---|
| English | ○ | ○ | ○ | ○ | ○ |
| Spanish | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |
| Other, please specify | ○ | ○ | ○ | ○ | ○ |

Please indicate your proficiency in reading for all the languages that you know.

| | Not at all proficient | Somewhat proficient | Moderately proficient | Quite proficient | Fluent |
|---|---|---|---|---|---|
| English | ○ | ○ | ○ | ○ | ○ |
| Spanish | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |

Please indicate your proficiency in listening for all the languages that you know.

| | Not at all proficient | Somewhat proficient | Moderately proficient | Quite proficient | Fluent |
|---|---|---|---|---|---|
| English | ○ | ○ | ○ | ○ | ○ |
| Spanish | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |
| Other, please specify _____ | ○ | ○ | ○ | ○ | ○ |

Where was your mother or female guardian born?

Where was your father or male guardian born?

What languages can your parents speak fluently?

| | Language(s) |
|---|---|
| Mother or female guardian | |
| Father or male guardian | |

If you speak two languages fluently, please complete the following questions. If your first language is not English, or if it is both English and something else, please treat the other language as your first language (L1) and English as your second language (L2) for these questions. Otherwise, treat English as your L1 and the other language as your L2. If you speak English and only English, you do not need to answer these questions, and may skip to the next page.

What is your L1?

What is your L2?

How did you learn your L2 (check all that apply):

- ☐ Mainly through formal classroom instruction
- ☐ Mainly through interacting with people
- ☐ Mainly from interacting with my parents
- ☐ Other (please specify):

Please indicate the number of years speaking:

|  | Number of years |
|---|---|
| Your L1 |  |
| Your L2 |  |
| Other (please specify): |  |

Please indicate the number of years of instruction received in:

|  | Number of years |
|---|---|
| Your L1 |  |
| Your L2 |  |
| Other (please specify): |  |

Please indicate your percent daily use of the following (total should equal 100%):

| | |
|---|---|
| Your L1 | 0 |
| Your L2 | 0 |
| Other (please specify): | 0 |
| **Total** | 0 |

Please indicate how often you:

| | Never | Less than Once a Month | 1-3 Times a Month | 1-3 Times a Week | 4-6 Times a Week | Daily, but not exclusively | Always |
|---|---|---|---|---|---|---|---|
| Speak L1 at home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Speak L1 at work/school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Speak L1 with friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Speak L2 at home | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Speak L2 at work/school | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Speak L2 with friends | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

What language(s):

| | Language(s) |
|---|---|
| Do your parents usually speak to each other at home? | |
| Do you usually speak to your mother at home? | |
| Do you usually speak to your father at home? | |
| Is/was spoken at home? | |
| Is/was spoken at school? | |

Please specify the age at which you started to learn your L2 in the following situations (write age next to any situation that applies):

| | Age |
|---|---|
| At home | |
| In school | |
| After arriving in a country speaking your L2 | |

Estimate, in terms of percentages, how often you use your native language and other languages per day in all daily activities combined (total should equal 100%):

| | |
|---|---|
| L1 | 0 |
| L2 | 0 |
| Other (please specify): | 0 |
| **Total** | 0 |

Estimate, in terms of hours per day, how often you watch TV or listen to the radio in your native language and other languages per day.

|  | Number of hours |
| --- | --- |
| L1 |  |
| L2 |  |
| Other (please specify): |  |

Estimate, in terms of hours per day, how often you read newspaper, magazines, and other general reading materials in your native language and other languages per day.

|  | Number of hours |
| --- | --- |
| L1 |  |
| L2 |  |
| Other (please specify): |  |

In what languages do you usually:

|  | List language |
| --- | --- |
| Add, multiply, and do simple arithmetic? |  |
| Dream? |  |
| Express anger or affection? |  |

When you are speaking, do you ever mix words or sentences from the two or more languages you know?

If yes, please list the languages that you mix and rate the frequency of mixing normal conversation with the following people on a scale from 1 (mixing is very rare) to 5 (mixing is very frequent).

|  | Languages mixed | Frequency of Mixing |
| --- | --- | --- |
| Spouse/family members |  |  |
| Friends |  |  |
| Co-workers |  |  |

In which language (among your best two languages) do you feel you usually do better? Write the name of the language under each condition:

|  | At home | At school/work |
| --- | --- | --- |
| Reading |  |  |
| Writing |  |  |
| Speaking |  |  |
| Understanding |  |  |

Among the languages you know, which language is the one that you would prefer to use in these situations?

|  | Language |
|---|---|
| At home | |
| At school/work | |
| At a party | |
| In general | |

If you have taken a standardized test of proficiency for languages other than your native language (e.g., TOEFL or Test of English as a Foreign Language), please indicate the scores you received for each.

|  | Name of Language | Name of Test | Test Score |
|---|---|---|---|
| Test 1 | | | |
| Test 2 | | | |
| Test 3 | | | |

*Example Sentence Items and Probes. Critical items are labeled with sentence type for one list version, but type was reversed on the counterbalanced version.*

| Type | Item | Probe |
|---|---|---|
| Subject-first | Este es el cardinal que presentó al/el obispo a los creyentes. | El cardinal presentó al obispo./El obispo presentó al cardenal. |
| Subject-first | Este es el general que vigilaba al/el espía desde la ventana. | El espía vigilaba al general./El general vigilaba al espía. |
| Subject-first | Este es el biólogo que visitaba al/el químico cada dos años. | El químico visitaba al biólogo./El biólogo visitaba al químico. |
| Subject-first | Este es el decano que mencionó al/el profesor en su discurso. | El decano mencionó al profesor./El profesor mencionó al decano. |
| Subject-first | Este es el cantante que admira al/el escritor por su elocuencia. | El escritor admira al cantante./El cantante admira al escritor. |
| Subject-first | Esta es la mujer que besaba al/el piloto en el aeropuerto. | El piloto besaba a la mujer./La mujer besaba al piloto. |
| Subject-first | Este es el senador que consultó al/el alcalde sobre la elección. | El alcalde consultó al senador./El senador consultó al alcalde. |
| Subject-first | Este es el político que defendió al/el redactor en el periódico. | El político defendió al redactor./El redactor defendió al político. |
| Object-first | Este es el gerente que fastidiaba el/al constructor con sus preguntas. | El constructor fastidiaba al gerente./El gerente fastidiaba al constructor. |
| Object-first | Este es el cajero que cuestionaba el/al gerente sobre el inventario. | El cajero cuestionaba al gerente./El gerente cuestionaba al cajero. |
| Object-first | Esta es la enfermera que apoyó el/al celador en su trabajo. | El celador apoyó a la enfermera./La enfermera apoyó al celador. |
| Object-first | Este es el motorista que seguía el/al camionero a la distancia. | El motorista seguía al camionero./El caminero seguía al motorista. |
| Object-first | Este es el músico que despertó el/al cantante con la melodía. | El cantante despertó al músico./El músico despertó al cantante. |
| Object-first | Este es el guionista que mencionó el/al productor hace unas semanas. | El guionista mencionó al productor./El productor mencionó al guionista. |
| Object-first | Este es el ladrón que retuvo el/al joyero durante tres horas. | El ladrón retuvo al joyero./El joyero retuvo al ladrón. |
| Object-first | Esta es la niñera que abraza el/al pequeño antes de despedirse. | La niñera abraza al pequeño./El pequeño abraza a la niñera. |
| Filler | El nuevo actor admiraba las películas del famoso director. | El director era poco conocido. |

| Filler | Los árboles del parque al lado de la escuela ocultaban al merodeador. | El merodeador se ocultaba dentro de la escuela. |
|--------|-----------------------------------------------------------------------|-------------------------------------------------|
| Filler | El zumo empapó el mantel y se filtró por la alfombra. | El mantel se quedó empapado. |
| Filler | La reina quería ser o piloto de avión o médico. | La reina quería ser dentista. |
| Filler | El ministro tomó el avión del empresario durante la emergencia. | El empresario tomó el avión. |
| Filler | La familia con perro cuidaba a las mascotas de sus vecinos. | La familia tenía una mascota. |
| Filler | El cachorro jugó con los niños del entrenador toda la tarde. | El entrenador jugó con el cachorro. |
| Filler | El comerciante no confiaba en la justicia después del juicio. | El comerciante confiaba en la justicia. |
| Filler | El avión y el barco impresionaron a los ingenieros. | El barco impresionó a los ingenieros. |
| Filler | Aquel granjero experimentado conduce el tractor nuevo. | El tractor nuevo es conducido por el granjero experimentado. |
| Filler | El coche del médico está mal aparcado frente a la casa. | El coche está aparcado en el hospital. |
| Filler | Luis cortejaba a la nieta de la pescadora con flores y canciones. | Luis cortejaba a la nieta. |
| Filler | Las clientas exigieron una rebaja en el precio después de saber más del producto. | Las clientas estaban satisfechas con el precio. |
| Filler | El nuevo avión fue diseñado por el exitoso ingeniero. | El ingeniero diseñó el avión. |
| Filler | El profesor y el estudiante leyeron el texto juntos. | El profesor leyó el texto solo. |
| Filler | Los prisioneros fueron liberados por los guerrilleros después de un mes en cautiverio. | Los policías liberaron a los prisioneros. |

*Example stimuli lists for high- and no-conflict N-back tasks*

| Item Order | N-back version | | | |
|---|---|---|---|---|
| | High-conflict | | No-conflict | |
| | **Trial Type** | **Stimulus** | **Trial Type** | **Stimulus** |
| 1 | non-target | calidad | non-target | lástima |
| 2 | non-target | pieza | non-target | bloque |
| 3 | lure | calidad | non-target | prenda |
| 4 | non-target | prodigio | non-target | volumen |
| 5 | target | pieza | target | bloque |
| 6 | target | calidad | target | prenda |
| 7 | target | prodigio | target | volumen |
| 8 | target | pieza | non-target | pobreza |
| 9 | non-target | suceso | non-target | canal |
| 10 | lure | calidad | target | volumen |
| 11 | lure | suceso | target | pobreza |
| 12 | lure | prodigio | non-target | salud |
| 13 | lure | pieza | non-target | manía |
| 14 | lure | calidad | non-target | episodio |
| 15 | target | prodigio | non-target | creador |
| 16 | target | pieza | target | manía |
| 17 | target | calidad | target | episodio |
| 18 | lure | pieza | target | creador |
| 19 | lure | calidad | non-target | calidad |
| 20 | non-target | escena | non-target | ritmo |
| 21 | target | pieza | non-target | máquina |
| 22 | target | calidad | non-target | masa |
| 23 | target | escena | non-target | tarea |
| 24 | target | pieza | non-target | claridad |
| 25 | target | calidad | target | masa |
| 26 | target | escena | target | tarea |
| 27 | non-target | cola | target | claridad |
| 28 | target | calidad | target | masa |
| 29 | target | escena | target | tarea |
| 30 | target | cola | non-target | dato |
| 31 | lure | escena | non-target | figura |
| 32 | lure | calidad | non-target | lentitud |
| 33 | target | cola | non-target | animal |
| 34 | lure | calidad | non-target | agente |
| 35 | lure | escena | non-target | medida |
| 36 | target | cola | non-target | dureza |
| 37 | target | calidad | target | agente |
| 38 | lure | cola | target | medida |
| 39 | lure | calidad | target | dureza |
| 40 | lure | escena | non-target | placer |
| 41 | lure | calidad | non-target | dulzura |
| 42 | lure | cola | non-target | detalle |

| 43 | target | escena | non-target | período |
|---|---|---|---|---|
| 44 | lure | cola | target | dulzura |
| 45 | non-target | ocio | target | detalle |
| 46 | target | escena | target | período |
| 47 | target | cola | target | dulzura |
| 48 | target | ocio | target | detalle |
| 49 | target | escena | target | período |
| 50 | target | cola | target | dulzura |
| 51 | lure | escena | non-target | reacción |
| 52 | lure | ocio | non-target | tránsito |
| 53 | target | cola | target | dulzura |
| 54 | target | escena | target | reacción |
| 55 | lure | cola | target | tránsito |
| 56 | lure | escena | non-target | símbolo |
| 57 | non-target | quietud | non-target | núcleo |
| 58 | target | cola | non-target | belleza |
| 59 | lure | quietud | non-target | emoción |
| 60 | lure | escena | non-target | sabor |
| 61 | lure | quietud | target | belleza |
| 62 | lure | cola | target | emoción |
| 63 | target | escena | target | sabor |
| 64 | target | quietud | non-target | quietud |
| 65 | lure | escena | target | emoción |
| 66 | non-target | igualdad | target | sabor |
| 67 | target | quietud | target | quietud |
| 68 | target | escena | target | emoción |
| 69 | target | igualdad | non-target | tensión |
| 70 | target | quietud | non-target | trance |
| 71 | target | escena | non-target | compañía |
| 72 | lure | quietud | non-target | cola |
| 73 | non-target | bloque | target | trance |
| 74 | lure | igualdad | target | compañía |
| 75 | target | quietud | target | cola |
| 76 | target | bloque | target | trance |
| 77 | target | igualdad | non-target | ruptura |
| 78 | lure | bloque | non-target | religión |
| 79 | lure | quietud | non-target | peligro |
| 80 | target | igualdad | target | ruptura |
| 81 | target | bloque | target | religión |
| 82 | target | quietud | target | peligro |
| 83 | non-target | belleza | target | ruptura |
| 84 | target | bloque | target | religión |
| 85 | lure | igualdad | non-target | rumor |
| 86 | target | belleza | non-target | peste |
| 87 | target | bloque | non-target | servicio |
| 88 | non-target | unión | non-target | suceso |
| 89 | lure | igualdad | target | peste |
| 90 | lure | belleza | target | servicio |
| 91 | lure | igualdad | target | suceso |

| 92 | lure | bloque | non-target | hallazgo |
|----|--------|----------|------------|----------|
| 93 | target | belleza | target | servicio |
| 94 | target | igualdad | non-target | vistazo |
| 95 | target | bloque | target | hallazgo |
| 96 | target | belleza | target | servicio |

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