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Cognitive control in bilinguals: Advantages in Stimulus–Stimulus inhibition*

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Abstract

Bilinguals have been shown to outperform monolinguals at suppressing task-irrelevant information and on overall speed during cognitive control tasks. Here, monolinguals' and bilinguals' performance was compared on two nonlinguistic tasks: a Stroop task (with perceptual Stimulus–Stimulus conflict among stimulus features) and a Simon task (with Stimulus–Response conflict). Across two experiments testing bilinguals with different language profiles, bilinguals showed more efficient Stroop than Simon performance, relative to monolinguals, who showed fewer differences across the two tasks. Findings suggest that bilingualism may engage Stroop-type cognitive control mechanisms more than Simon-type mechanisms, likely due to increased Stimulus–Stimulus conflict during bilingual language processing. Findings are discussed in light of previous research on bilingual Stroop and Simon performance.

Keywords

bilingualism; inhibition; Stroop task; Simon task

Bilingualism has been associated with performance advantages across various cognitive tasks, including Stroop (e.g., Bialystok, Craik & Luk, 2008; Carlson & Meltzoff, 2008; Hernández, Costa, Fuentes, Vivas & Sebastián-Gallés, 2010) and Simon tasks (e.g., Bialystok, Craik, Klein & Viswanathan, 2004; Salvatierra & Rosselli, 2011). On the classic Stroop task, participants are presented with color words, and are instructed to name the color of the ink as rapidly as possible. If the word *blue* is written in BLUE ink, then there is congruence of information; however, if the word *green* is written in BLUE ink, then there is

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incongruence and conflict of information. On the classic Simon task, participants press a right key to respond to a blue-color square or a left key to respond to a red-color square. Conflict arises when the blue-color square (requiring a RIGHT-key press) appears on the LEFT or the red-color square (requiring a LEFT-key press) appears on the RIGHT.

Bilingual advantages are not always found in young adults (e.g., Hilchey & Klein, 2011). However, Stroop-type advantages have been identified more frequently in young bilingual adults (Bialystok et al., 2008; Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009; Costa, Hernández & Sebastián-Gallés, 2008; Hernández et al., 2010; Luk, de Sa & Bialystok, 2011, see Table 1 for an overview) compared to Simon-type advantages (e.g., Bialystok, 2006; Morton & Harper, 2007). Simon-type advantages appear to be more constrained to children (Bialystok, Martin & Viswanathan., 2005, Martin-Rhee & Bialystok, 2008) and older adults (Bialystok et al., 2004; Salvatierra & Rosselli, 2011, Schroeder & Marian, 2012, see Table 2 for an overview). This task difference may be a result of bilingualism influencing some aspects of cognitive control more than others, which is likely the case since cognitive advantages are thought to emerge due to specific linguistic demands in bilinguals (e.g., Bialystok & Craik, 2010; Kroll, 2008). To examine the extent to which Stroop-type and Simon-type cognitive control mechanisms are engaged and shaped by bilingual experience, bilinguals' and monolinguals' performance on these two types of inhibitory control are compared in the current study.

Differences between Stroop-type (MacLeod, 1991, Stroop, 1935) and Simon-type inhibition (Simon & Rudell, 1967) can be examined within the context of the Dimensional Overlap Model (Kornblum, Stevens, Whipple & Requin, 1999), a model that accounts for a variety of different inhibition mechanisms. On the classic Stroop task, there are two stimulus dimensions: the color of a word's ink (e.g., blue, green) and the meaning of the word (e.g., *blue*, *green*). The Dimensional Overlap Model posits that this conflict between two dimensions of the same stimulus (i.e., Stimulus–Stimulus conflict) originates and is resolved at the perceptual level of word representations (*blue*, *green*). In contrast, the pure Simon task is conceptualized within the Dimensional Overlap Model as a task where no overlap is present between perceptual dimensions of the same stimulus (stimulus color and stimulus location). Instead, overlap is present between the stimulus dimension that is irrelevant to the response rule (e.g., stimulus location: right, left), and the response dimension (e.g., right key, left key, Kornblum, 1994). In short, conflict is created between two alternative Stimulus–Response mappings.¹

Despite the apparent absence of bilingual advantages on pure Simon tasks in young adults (i.e., 20–30-year-olds), it is likely that there are more subtle differences on Simon performance between young monolinguals and bilinguals. For example, Bialystok, Craik, Grady et al. (2005) found that neural networks associated with Simon performance differed

¹Some studies that yielded bilingual Simon advantages employed a task version that also contains overlap between stimulus dimensions (e.g., Bialystok, 2006; Bialystok & DePape, 2009). This task is the Spatial Arrows Task (and has been referred to as both Spatial Stroop Task and Spatial Simon Task, e.g. Hilchey & Klein, 2011). A right- or left- pointing arrow appears to the right or to the left of a central fixation cross. Participants identify the direction of the arrow by pressing a key on either the right or the left side of the keyboard. As a result, the two stimulus dimensions, as well as the response dimension, have overlapping attributes on this task (*right*, *left*). Within the Dimensional Overlap Model, this task assembly is categorized as a classic Stroop Task (Kornblum, 1994), and we refer to it as a Spatial Stroop Task in the present paper.

between young monolinguals and bilinguals, despite an absence of behavioral differences between the French–English bilingual and monolingual participants. Along similar lines, Linck, Schwieter, and Sunderman (2012) found that smaller Simon effects in trilingual young adults correlated with a smaller switching cost from L2 or L3 into L1. In contrast, clear cognitive Stroop advantages have been found across a number of studies with young bilingual participants (Bialystok, 2006; Bialystok et al., 2008; Bialystok & DePape, 2009; Costa et al., 2008; Hernández et al., 2010), and performance on the spatial Stroop task has been linked to conflict resolution during auditory word comprehension in bilinguals (Blumenfeld & Marian, 2011, 2013). Mercier, Pivneva and Titone (2014) show a link between auditory word recognition in bilinguals and a composite cognitive control measure including two tasks with Stimulus–Stimulus conflict (the spatial Stroop task employed here and a number Stroop task) as well as a task with only Stimulus–Response conflict (the Simon task employed here). Taken together, while both Stimulus–Response (Simon-type) performance and Stimulus–Stimulus (Stroop-type) performance have been linked to bilingual language processing, it is possible that advantages on pure Simon tasks may be more subtle and limited compared to advantages on tasks that incorporate Stimulus–Stimulus conflict. The possibility that there are differences between bilinguals’ Stroop and Simon performance is consistent with previously-identified neural differences between the two tasks in monolinguals (e.g., Egner, 2008; Liu, Banich, Jacobson & Tanabe, 2004).

Experiment overview and hypotheses

The aim of the present study is to tease apart Stimulus–Stimulus and Stimulus–Response inhibition in bilinguals relative to performance patterns in monolinguals, by comparing performance on Stroop-type and Simon-type inhibitory control tasks. The nonlinguistic spatial Stroop task employed in the present study was also used by Blumenfeld and Marian (2011, 2013) and is highly similar to the tasks employed by Bialystok (2006) and Bialystok and DePape (2009). To examine whether perceptual overlap of stimulus dimensions on this nonlinguistic Stroop task created an inhibition context that is particularly sensitive to bilingual experience, participants’ performance on this task was contrasted with performance on a spatial and nonlinguistic Simon task. Importantly, the spatial Stroop and Simon tasks were designed to be highly similar to each other in terms of visual input, stimulus dimensions, task requirements, and timing. Therefore, performance differences between the tasks can be ascribed to differences in overlap between the two stimulus dimensions.² On the Simon task, the two perceptual stimulus dimensions of ARROW LOCATION (right, left) and ARROW DIRECTION (up, down) did not overlap and no conflict was present between perceptual dimensions of the same stimulus. Instead, conflict was created when the irrelevant stimulus dimension overlapped with the response dimension (right key, left key), creating two competing response options. In sum, in the current Stroop task, the Stroop-characteristic perceptual overlap between stimulus dimensions was maintained, while in the Simon task this overlap was absent.

²There was also overlap between the RELEVANT stimulus dimension (arrow direction) and the response dimension (*right, left*) on the Stroop but not the Simon task. This is a commonly-found difference between Stroop and Simon tasks (Kornblum, 1994; i.e., Simon tasks have an arbitrary response rule). However, this difference is the source of neither Stimulus–Stimulus conflict nor Stimulus–Response conflict (the latter arises due to overlap between the IRRELEVANT stimulus dimension and the response dimension).

It was reasoned that, in bilinguals, differences would emerge between the Stroop and Simon tasks because bilingual language processing may rely more heavily on Stimulus–Stimulus inhibition than on Stimulus–Response inhibition as a result of cross-linguistic competition that is resolved at the lexical level. Within the framework of the Dimensional Overlap Model (Kornblum, 1994), Stimulus–Stimulus inhibition refers to conflict between co-activated language representations. In contrast, Stimulus–Response inhibition refers to conflict between two overt responses if cross-linguistic conflict has not been resolved by the time the response stage is reached. Models of bilingual language processing suggest involvement of inhibition mechanisms at various levels of bilingual processing, typically focusing on the lexical level, where cross-linguistic competition is hypothesized to be resolved via inhibition (Dijkstra & Van Heuven, 1998; Green, 1986, 1998; Grosjean, 1997; Shook & Marian, 2013).

Stimulus–Stimulus inhibition is likely to be recruited for bilingual language comprehension as well as production processes. During the early stages of bilingual language comprehension, phonological and lexical representations that match auditory input have been shown to be activated cross-linguistically (e.g., Blumenfeld & Marian, 2007; Marian & Spivey, 2003a, 2003b; Weber & Cutler, 2004). For example, when participants hear /pɛ/-, they might activate the English word *pebble* as well as the Spanish word *perro* “dog”. In this sense, the initially perceived signal, /pɛ/-, is ambiguous. Such perceptual conflict has been extensively documented during language comprehension, both within languages (e.g., *can-candy*, Blumenfeld & Marian, 2011; Marian & Spivey, 2003b) and between languages (e.g., Blumenfeld & Marian, 2007; 2013; Macizo, Bajo & Martín, 2010; Marian & Spivey, 2003a, b; Martín, Macizo & Bajo, 2010). Models of bilingual language comprehension suggest that, as similar-sounding words compete within a cross-linguistically integrated lexicon, inhibitory control can be applied to competitors in the process of word identification (e.g., Shook & Marian, 2013). This Stimulus–Stimulus type of inhibition is driven by perceptual similarity of word candidates within and across languages, resulting in competition at the lexical level.

In addition to comprehension, cross-linguistic conflict is also likely to arise during bilingual language production. During production, cross-linguistic co-activation and competition have been shown between representations at the concept level, the lemma level, the phonological level, and the speech planning level (for a review, see Kroll, Bobb & Wodniecka, 2006). For example, during picture naming, words that sound similar to the translation-equivalents of naming-targets have been shown to create interference (Hermans, Bongaerts, de Bot & Schreuder, 1998), suggesting lemma-level cross-linguistic competition. Similarly, cross-linguistic homophones are named slower than non-homophones, and Kroll, Dijkstra, Janssen and Schriefers (2000) have suggested that this effect is due to co-activated phonologies (e.g., English *leaf* and Dutch *lief* “nice”), which in turn trigger bottom–up activation of competing lemmas and conceptual representations that will compete for selection. Kroll et al. (2006, p. 126) have referred to scenarios such as these as “internally generated Stroop effect[s]”. With cross-linguistically integrated lexical representations, they have argued, competition and selection for production may occur at various loci throughout the representational hierarchy, depending on factors such as proficiency and context. In terms of the Dimensional Overlap

Model, bilingual language production can therefore be argued to recruit both Stimulus–Stimulus and Stimulus–Response inhibition mechanisms. In this case, Stimulus–Stimulus inhibition refers to language-internal inhibition of competing representations at the concept and lexical levels. In turn, Stimulus–Response inhibition refers to inhibition of a competing response if two production options do remain co-active and compete for selection at the output level (i.e., at the response planning stages).

Although both Stimulus–Stimulus and Stimulus–Response conflict are likely present during bilingual production, it can be reasoned that they do not always arise together. For example, bilinguals who operate in their most proficient language and in a unilingual context may co-activate both languages up to the lemma level, with cross-linguistic competition resolved at this stage and with language-selective processing at the output level (Costa & Santesteban, 2004). In such a context, Stimulus–Stimulus competition is present, but Stimulus–Response competition may not be involved. Language switching contexts provide an alternative example: When bilinguals expect to switch between languages, different-language output options are likely co-active and compete for selection. Language switching has indeed been found to correlate with Stimulus–Response inhibition indexed by the Simon task (e.g., Linck et al., 2012).

Considering cross-linguistic competition during both bilingual comprehension and production, we reasoned that Stimulus–Stimulus competition would be most susceptible to bilingual influences. Although Stimulus–Response inhibition may also be more likely in bilinguals vs. monolinguals, Stimulus–Stimulus competition may be the most common type of bilingual competition because lexical between-language competition is present during both comprehension and production, while Stimulus–Response inhibition may be limited to production contexts where both languages remain active until the response stage. Because cross-linguistic co-activation may result in Stimulus–Stimulus competition more frequently than in Stimulus–Response competition, we predicted that bilinguals would perform best on the Stroop task, relative to the Simon task and relative to monolingual Stroop performance.

In sum, it was predicted that, if bilingual language processing places particular demands on Stimulus–Stimulus inhibition, then enhanced bilingual performance should be found on the nonlinguistic Stroop task relative to the nonlinguistic Simon inhibition task. As a result, performance differences between Stroop and Simon tasks were predicted to be more pronounced in bilinguals than in monolinguals. Conversely, if bilingual language processing makes equal use of a broad range of inhibitory control processes, including inhibition of competing Stimulus–Response mappings, then bilinguals' performance should be similar across Stroop and Simon tasks, and patterns of Stroop vs. Simon performance should be similar for bilinguals and monolinguals.

Experiment 1: Identification of a Bilingual Stroop (Stimulus–Stimulus) – Simon (Stimulus–Response) Dissociation in Bilinguals vs. Monolinguals

To examine whether bilingual experience influences Stroop-type (Stimulus–Stimulus) inhibition more than Simon-type (Stimulus–Response) inhibition, a group of bilinguals and a group of monolinguals were compared on nonlinguistic Stroop and Simon tasks. Since

highly proficient bilinguals have been found to be more likely to show cognitive advantages relative to monolinguals (e.g., Luk et al., 2011; Singh & Mishra, 2012), early proficient bilinguals were chosen. The nonlinguistic Stroop task selected for the current study had previously been associated with bilingual experience (Bialystok, 2006; Bialystok & DePape, 2009; Blumenfeld & Marian, 2011, 2013). In order to create a direct comparison between Stimulus–Stimulus inhibition and Stimulus–Response inhibition, a nonlinguistic Simon task was selected that was highly similar to the Stroop task.

Method

Participants—Thirty English–Spanish bilinguals ($M_{age} = 22.0$ years, range 18–38 years, $SD = 5.2$; 9 males) and 30 English monolinguals ($M_{age} = 21.4$ years, range 18–33 years, $SD = 3.9$; 6 males) were tested at a large private university in the Midwestern United States. Bilinguals and monolinguals were matched on age, $t(58) = 0.5$, $p > .5$, English receptive vocabulary (assessed by the Peabody Picture Vocabulary Task, Dunn and Dunn (1997); bilinguals: $M = 116.2$, $SD = 12.2$; monolinguals: $M = 116.7$, $SD = 11.7$; $t(58) = 0.1$, $p > .5$), expressive vocabulary (assessed by letter and semantic category verbal fluency tasks: letter fluency – bilinguals: $M = 13.3$, $SD = 2.7$; monolinguals: $M = 13.9$, $SD = 3.4$; $t(58) = 0.7$, $p > .4$; category fluency – bilinguals: $M = 16.4$, $SD = 3.0$; monolinguals: $M = 16.7$, $SD = 4.5$; $t(58) = 0.3$, $p > .5$), digit span (assessed by a digit span task, Wagner, Torgesen and Rashotte (1999); bilinguals: $M = 17.6$, $SD = 2.5$; monolinguals: $M = 17.5$, $SD = 2.1$; $t(58) = 0.2$, $p > .5$), and nonverbal IQ (assessed by the Wechsler Abbreviated Scale of Intelligence (WASI), PsychCorp (1999); bilinguals: $M = 110.0$, $SD = 11.7$; monolinguals: $M = 110.5$, $SD = 11.8$; $t(58) = 0.2$, $p > .5$). Monolinguals ($M = 9.6$, $SD = 0.5$) and bilinguals ($M = 9.4$, $SD = 0.7$) did not differ on self-reported English proficiency across comprehension, speaking, and reading modalities, $t(58) = 1.4$, $p > .1$. Bilingual English–Spanish participants spoke English as a native language and rated their Spanish proficiency at 7.7 on a scale from 0 to 10 ($SD = 1.1$, where 0 = “no proficiency” and 10 = “perfect proficiency”) across comprehension, speaking, and reading modalities. Bilinguals had acquired Spanish at the average age of 2.9 years ($SD = 3.8$) and were currently exposed to Spanish 20.5% of the time ($SD = 13.4$). On the expressive vocabulary verbal fluency tasks, bilinguals performed significantly better in English than in Spanish (Spanish letter fluency = 9.7, $SD = 3.0$; Spanish category fluency = 8.8, $SD = 3.7$; $t(29) = 6.7$, $p < .001$). Monolinguals had only minimal exposure to foreign languages ($M = 1.8\%$ of the time, $SD = 2.7$).

Study design—The current study followed a $2 \times 2 \times 2$ design, with TRIAL TYPE (incongruent, congruent) and TASK (nonlinguistic Stroop task, nonlinguistic Simon task) as within-subject factors, and Group (monolingual, bilingual) as a between-subjects factor. The dependent variables were response accuracies and latencies. In addition, difference scores were calculated comparing performance on incongruent vs. congruent trials (i.e., Stroop and Simon effects, indexing the extent of inhibition of conflicting information during incongruent Stimulus–Stimulus or Stimulus–Response contexts).

Materials—The NONLINGUISTIC Stroop TASK employed in the present study was adapted from previous studies (Bialystok, 2006; Liu et al., 2004) and was also used in Blumenfeld and Marian (2011). The two stimulus dimensions ARROW DIRECTION and

ARROW LOCATION were manipulated to be either congruent or incongruent. Participants were asked to respond to arrow direction but to ignore location. They were instructed to press a response-key located on the left side of the keyboard when they saw a leftward-facing arrow, and a response-key on the right when they saw a rightward-facing arrow. Sixty congruent trials contained a leftward-facing arrow presented to the left of the central fixation cross, and 60 contained a rightward-facing arrow presented to the right of the central fixation cross. Twenty incongruent trials contained a leftward-facing arrow presented to the right of the central fixation cross, and 20 contained a rightward-facing arrow presented to the left of the central fixation cross. See Figure 1 (panels A–B) for an illustration of this task.

On the NONLINGUISTIC Simon TASK, response conflict was created by varying the irrelevant stimulus dimension arrow location (right, left) and the response dimension (right-key press, left-key press) to be either congruent or incongruent. Participants monitored and responded to the stimulus dimension ARROW DIRECTION (e.g., upward-pointing, downward-pointing). They were instructed to press a response key located on the left side of the keyboard when they saw an upward-facing arrow, and to press a response key located on the right when they saw a downward-facing arrow. Participants were also instructed to ignore the location of the arrows. For example, response conflict was created when the stimulus occurred on the left side and was a downward-pointing arrow (in this case, participants might follow the location cue and press the LEFT response key, even though the correct response was the RIGHT key). Sixty congruent trials contained an upward-facing arrow presented to the left of the central fixation cross, and 60 contained a downward-facing arrow presented to the right of the central fixation cross. Twenty incongruent trials contained an upward-facing arrow presented to the right of the central fixation cross, and 20 contained a downward-facing arrow presented to the left of the central fixation cross. See Figure 1 (panels C–D) for an illustration of this task.

For both the Stroop and Simon tasks, the ratio of incongruent to congruent trials was maintained at 1:3, and each trial started with a 500 ms central fixation cross (to call participants' attention towards the middle of the screen), followed by a 700 ms presentation of the congruent or incongruent stimulus display, and an 800 ms presentation of a blank screen. All trials were presented in a fixed pseudo-randomized order.

Procedure—Monolinguals and bilinguals completed the nonlinguistic Stroop and Simon tasks (with the order of presentation of the two tasks counterbalanced across participants). Participants were instructed to respond by pressing two keys on the keyboard using their right and left index fingers. Before starting each task, participants read instructions on the screen; in addition, the experimenter verbally explained each task. Following instructions, participants completed 20 trials where the relevant stimulus was placed in the center of the screen (i.e., an arrow pointing right or left for the Stroop task and an arrow pointing up or down for the Simon task). Participants were then instructed (both verbally and via text on the screen) that, on the following task, they should respond exactly as they had practiced, that the stimulus would appear at different locations on the screen, and that they should ignore these changes in location as much as possible. Participants were instructed to respond as rapidly and accurately as possible. Participants also completed the Language Experience

and Proficiency Questionnaire (Marian, Blumenfeld & Kaushanskaya, 2007) and provided self-reported proficiency ratings and the percentage of time they were exposed to each language on a daily basis.

To measure proficiency in both languages, participants were administered the receptive Peabody Picture Vocabulary Test (PPVT–III; Dunn & Dunn, 1997, and its Spanish equivalent, the Test de Vocabulario en Imágenes Peabody; Dunn, Padilla, Lugo & Dunn, 1986), and verbal fluency tasks. On verbal fluency tasks, participants responded to cues to list as many words as possible that started with a given letter within 60 seconds, and to semantic category cues to list as many words as possible that belonged to a given category within 60 seconds. In English, half of all participants received letter cues *E*, *P*, and *M*, and the other half received letters *A*, *L*, and *C*. Half of all participants received category cues “animals”, “vegetables”, and “clothes”, and the other half received “colors”, and “fruits”. In Spanish, bilingual participants received letter and category sets that they had not seen in English. In addition, participants were administered the digit span subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999), and the performance subtests of the WASI, PsychCorp, 1999). All participants were tested in English first, followed by language testing in Spanish.

Data coding—Decision accuracies and latencies on congruent vs. incongruent trials were captured by using Superlab software. For each participant, incorrect responses were removed from consideration when response latencies were analyzed. Response latencies below 200 ms and values below or above 2.5 standard deviations from the mean were also removed. This procedure resulted in the omission of 2.5% of data.

Results

To compare monolinguals’ and bilinguals’ performance across Simon and Stroop measures, a $2 \times 2 \times 2$ mixed ANOVA was conducted, with trial type (incongruent, congruent) and task (nonlinguistic Stroop task, nonlinguistic Simon task) as within-subject factors, and group (monolingual, bilingual) as a between-subjects factor. Results are presented separately for accuracy rates and response latencies, including follow-up analyses.

Accuracy rates—Results yielded a main effect of trial type, $F(1,58) = 160.6, p < .0001, \eta_p^2 = .7$, suggesting that participants were overall less accurate responding to incongruent Stroop and Simon trials ($M = 82.7\%$, $SE = 1.3$) than to congruent trials ($M = 98.8\%$, $SE = 0.3$). Performance accuracy was equivalent on nonlinguistic Stroop ($M = 91.8\%$, $SE = 0.8$) and Simon tasks ($M = 89.7\%$, $SE = 1.0$), $F(1,58) = 3.1, p = .08, \eta_p^2 = .05$. No main effect of group was observed, $F(1,58) = 0.4, p > .1, \eta_p^2 = .006$, suggesting that overall response accuracy rates were equal for monolinguals ($M = 90.3\%$, $SE = 1.0$) and bilinguals ($M = 91.2\%$, $SE = 1.0$). However, a three-way interaction emerged between trial type, task, and group, $F(1,58) = 5.0, p < .05, \eta_p^2 = .1$, together with a marginal two-way interaction between task and group, $F(1,58) = 3.8, p = .06, \eta_p^2 = .1$.

Follow-up 2×2 ANOVAs with competitor (incongruent, congruent) and task (nonlinguistic Stroop, nonlinguistic Simon) were conducted for each group separately. Monolinguals performed equivalently across the two tasks, with no main effect of task, $F(1,58) = 0.01, p$

$> .5$, $\eta_p^2 < .0001$, and no interaction between trial type and task, $F(1,58) = 0.08$, $p > .5$, $\eta_p^2 = .003$, see Figure 2. In contrast, bilingual participants showed a main effect of task, $F(1,58) = 8.7$, $p < .01$, $\eta_p^2 = .2$, and an interaction between trial type and task, $F(1,58) = 8.5$, $p < .01$, $\eta_p^2 = .2$. Follow-up t -tests revealed that bilinguals had higher overall accuracy rates on the nonlinguistic Stroop task ($M = 93.4\%$, $SE = 0.6$) than on the nonlinguistic Simon task ($M = 89.0\%$, $SE = 1.1$), $t(29) = 2.9$, $p < .01$. In addition, bilinguals showed a smaller difference between congruent and incongruent trials on the nonlinguistic Stroop task (difference score = 11.9%, $SE = 1.4$), than between congruent and incongruent trials on the nonlinguistic Simon task (difference score = 19.8%, $SE = 2.9$), $t(29) = 2.9$, $p < .01$, see Figure 2. Follow-up between-group analyses suggested that differences between Stroop and Simon effects in bilinguals, but not in monolinguals, were driven by monolingual–bilingual performance differences on incongruent Stroop trials, with bilinguals ($M = 87.4\%$, $SE = 1.6$) performing more accurately than monolinguals ($M = 81.8\%$, $SE = 2.6$) on these trials, $t(58) = 1.8$, $p = .038$ (one-tailed). In contrast, no monolingual–bilingual differences were found on incongruent Simon trials, or on congruent Stroop or Simon trials (all $ps > .1$).

Response latencies—When response latencies were analyzed with the $2 \times 2 \times 2$ mixed ANOVA, results yielded a main effect of trial type, $F(1,58) = 769.6$, $p < .0001$, $\eta_p^2 = .9$, suggesting that participants were overall slower on incongruent trials ($M = 475.5$ ms, $SE = 6.8$) than on congruent trials ($M = 380.1$ ms, $SE = 5.8$). In addition, a main effect of task, $F(1,58) = 11.4$, $p = .001$, $\eta_p^2 = .2$, showed that overall response times on the nonlinguistic Stroop task ($M = 418.9$ ms, $SE = 6.4$) were faster than overall response times on the Simon task ($M = 436.8$ ms, $SE = 6.6$). However, no main effect of group was observed, $F(1,58) = 0.007$, $p > .5$, $\eta_p^2 < .001$, suggesting that overall response latencies were equal for monolinguals ($M = 427.4$ ms, $SE = 8.6$) and bilinguals ($M = 428.3$ ms, $SE = 8.6$). Two-way interactions between task and group, $F(1,58) = 0.3$, $p > .5$, $\eta_p^2 = .005$, and three-way interactions between competitor, task, and group, $F(1,58) = 1.5$, $p > .1$, $\eta_p^2 = .03$, were not significant, suggesting that monolinguals and bilinguals had comparable response latencies across the two inhibition tasks.

Efficiency scores—To protect against speed–accuracy trade-offs in comparing the two groups, accuracy and reaction time data were combined into efficiency scores, which were calculated by dividing reaction times by accuracy proportions (Christie & Klein, 1995; Townsend & Ashby, 1983). Smaller efficiency scores are interpreted as more efficient performance, characterized by shorter reaction times and higher accuracy rates. Results of efficiency score analyses were similar to reported accuracy results and revealed main effects of trial (incongruent, congruent), $F(1,58) = 200.3$, $p < .001$, $\eta_p^2 = .8$, and task (Stroop, Simon), $F(1,58) = 6.8$, $p = .01$, $\eta_p^2 = .1$. In addition, a significant two-way interaction between task and group ($F(1,58) = 4.6$, $p < .05$, $\eta_p^2 = .1$) and a significant three-way interaction between trial, task, and group ($F(1,58) = 5.4$, $p < .05$, $\eta_p^2 = .1$) emerged. As in the accuracy analyses, separate follow-up analyses for monolinguals yielded no differences between Stroop and Simon tasks, $F(1,29) = 0.11$, $p > .5$, $\eta_p^2 = .004$, and no interaction between trial and task, $F(1,29) = 0.27$, $p > .5$, $\eta_p^2 = .009$. Conversely, follow-up analyses for bilinguals confirmed significant differences between Stroop ($M = 455.3$ ms/proportion correct, $SE = 11.9$) and Simon performance ($M = 528.5$ ms/proportion correct, $SE = 22.9$),

$F(1,29) = 12.4, p = .001, \eta_p^2 = .3$. Bilinguals also showed a significant interaction between trial and task, $F(1,29) = 6.5, p < .05, \eta_p^2 = .2$, with smaller Stroop effects (156.9 ms/proportion correct) than Simon effects (271.1 ms/proportion correct), $t(29) = 2.6, p < .05$. Finally, as previously, analyses suggested that differences between bilinguals and monolinguals were driven by performance differences on the Stroop task, with bilinguals ($M = 533.8$ ms/proportion correct, $SE = 17.3$) performing more efficiently than monolinguals ($M = 599.6$ ms/proportion correct, $SE = 32.9$) on incongruent Stroop trials, $t(58) = 1.9, p = .03$ (one-tailed), and with smaller Stroop effects in bilinguals (152.2 ms/proportion correct, $SE = 13.0$) than in monolinguals (217.0 ms/proportion correct, $SE = 28.9$), $t(58) = 2.1, p < .05$. Together, results suggest that bilinguals were more efficient at inhibiting irrelevant information on the Stroop task than on the Simon task.

Discussion

In Experiment 1, bilinguals' and monolinguals' performance was compared on nonlinguistic Stroop and Simon tasks that involved identification of arrow direction in the presence of congruent or incongruent location information. Within the bilingual group, an advantage was found on performance during the nonlinguistic Stroop task relative to the nonlinguistic Simon task and relative to monolingual Stroop performance. In contrast, monolinguals performed equivalently across the two tasks. These findings of bilinguals' better Stroop performance can be explained within the framework of the Dimensional Overlap Model. Specifically, the Stroop task generates perceptual Stimulus–Stimulus conflict based on a bivalent stimulus (e.g., a RIGHT-pointing arrow on the LEFT side of a display) that may be analogous to bilingual cross-linguistic lexical competition (e.g., Kroll et al., 2006; Shook & Marian, 2013). It is possible that resolution of Stimulus–Stimulus conflict is honed in bilinguals who experience both within-language and between-language ambiguity. To replicate the identified pattern of Stroop–Simon dissociations in a different group of bilinguals and to further examine the nature of Stroop vs. Simon effects, a second experiment was conducted. Critically, Experiment 2 contained an additional “neutral” condition in both the Stroop and Simon task where arrows appeared in the center of the screen. In this condition, participants were subject to neither interference effects (due to incongruent location information) nor facilitation effects (due to congruent location information). Therefore, presence of location-neutral trials would allow for identification of inhibition components of Stroop and Simon effects (incongruent vs. neutral trials) as well as identification of facilitation components (congruent vs. neutral trials). It was predicted that, as in Experiment 1, bilinguals would be overall more efficient on the Stroop task relative to the Simon task. In addition, if bilingual–monolingual differences would emerge in Stroop vs. Simon performance, then group-differences could be localized to the inhibition or facilitation components.

Experiment 2: Replication of a Bilingual Stroop (Stimulus–Stimulus) – Simon (Stimulus Response) Dissociation and the Role of Inhibition vs. Facilitation

In Experiment 2, we aimed to (1) replicate Experiment 1 findings of enhanced bilingual performance on the Stroop relative to the Simon task, and to (2) examine whether task and group differences could be localized to inhibition or facilitation components of the two tasks. A different bilingual group was recruited for Experiment 2 in order to examine the stability of the previously-observed effects across a heterogeneous population of bilinguals. Specifically, participants in Experiment 2 were Spanish–English early bilinguals tested at a large public university in Southern California. We predicted that previously-observed effects would maintain in the new group of bilinguals, relative to monolingual peers. In addition, based on previous findings (e.g., Van Heuven, Conklin, Coderre, Guo & Dijkstra, 2011), we expected a smaller magnitude of Stroop facilitation compared to Stroop inhibition. As a result, we predicted that bilingual effects would be driven by the inhibition component of the Stroop task.

Method

Participants—Sixty Spanish–English bilinguals ($M_{age} = 21.7$, range: 18–32, $SD = 3.1$; 6 males) and 60 English monolinguals ($M_{age} = 22.2$, range: 18–35, $SD = 3.8$; 8 males) participated. Bilinguals and monolinguals were matched on age, $t(118) = 0.9$, $p > .3$, English receptive vocabulary (assessed by the Peabody Picture Vocabulary Task (raw scores), Dunn & Dunn, 1997; bilinguals: $M = 176.2$, $SD = 8.4$; monolinguals: $M = 178.9$, $SD = 9.5$; $t(118) = 1.4$, $p > .1$), backward digit span (assessed by a backward digit span task, Woodcock, McGrew & Mather, 2001; bilinguals: $M = 16.6$, $SD = 3.9$; monolinguals: $M = 18.0$, $SD = 4.2$; $t(118) = 1.8$, $p = .07$), and nonverbal reasoning (assessed by the Matrix Reasoning component raw score of the WASI, PsychCorp, 1999; bilinguals: $M = 26.8$, $SD = 3.4$; monolinguals: $M = 27.4$, $SD = 3.8$, $t(118) = 1.1$, $p > .1$). Monolinguals ($M = 9.8$, $SD = 0.4$) and bilinguals ($M = 9.4$, $SD = 0.7$) differed on self-reported English proficiency across comprehension, speaking, and reading modalities, $t(118) = 3.8$, $p < .001$, and on expressive vocabulary (assessed by letter and semantic category verbal fluency tasks: letter fluency – bilinguals: $M = 12.6$, $SD = 3.3$; monolinguals: $M = 14.0$, $SD = 3.4$, $t(118) = 2.4$, $p < .05$; category fluency – bilinguals: $M = 14.2$, $SD = 3.4$, monolinguals: $M = 15.6$, $SD = 2.8$, $t(118) = 2.3$, $p < .05$). Bilingual Spanish–English participants spoke Spanish as a native language and rated their Spanish proficiency at 8.5 on a scale from 0 to 10 ($SD = 1.2$, where 0 = *no proficiency* and 10 = *perfect proficiency*) across comprehension, speaking, and reading modalities. Bilinguals had acquired English at the average age of 4.4 years ($SD = 2.8$), had become fluent in it at 7.0 years ($SD = 3.4$), and were currently exposed to Spanish 35.0% of the time ($SD = 16.8$). On the expressive vocabulary verbal fluency tasks, bilinguals performed significantly better in English than in Spanish (*Spanish letter fluency* = 11.8, $SD = 2.8$; *Spanish category fluency* = 10.9, $SD = 3.4$, $t(59) = 3.9$, $p < .001$). Monolinguals had only minimal exposure to foreign languages (1.4% of the time, $SD = 3.1$). Table 3 provides a direct comparison of bilinguals in Experiments 1 and 2.

Materials and procedure—In addition to the 120 congruent trials and 40 incongruent trials described in Experiment 1, both Stroop and Simon tasks also contained 40 neutral trials where the arrow appeared in the center of the display. The rationale for including the neutral trials was to separate out facilitation and inhibition components of the Stroop and Simon effects by providing a condition that contained neither congruent nor incongruent information. The neutral trials were intermixed with the other trial types. On the Stroop task, 20 neutral trials contained an arrow that pointed right and 20 neutral trials contained an arrow that pointed left. On the Simon task, 20 neutral trials contained an arrow that pointed upward and 20 neutral trials contained an arrow that pointed downward. All remaining procedures were identical to those in Experiment 1. Response latencies below 200 ms and values below or above 2.5 standard deviations from the mean were removed from analyses, resulting in omission of 1.9% of data.

Results

Accuracy rates—When data were analyzed with a 3 (condition: incongruent, congruent, neutral) \times 2 (task: Stroop, Simon) \times 2 (group: bilingual, monolingual) ANOVA, results confirmed a main effect of trial type (incongruent, congruent, neutral), $F(1,118) = 253.7$, $p < .001$, $\eta_p^2 = .7$, suggesting that participants were overall less accurate responding to incongruent Stroop and Simon trials ($M = 85.8\%$, $SE = 0.9$) than to congruent trials ($M = 98.2\%$, $SE = 0.3$) or to newly added neutral trials ($M = 94.5\%$, $SE = 0.5$). As in Experiment 1, performance accuracy was higher on the nonlinguistic Stroop task ($M = 94.5\%$, $SE = 0.6$) than on the Simon task ($M = 91.1\%$, $SE = 0.5$), $F(1,118) = 38.9$, $p < .001$, $\eta_p^2 = .3$, and no main effect of group was observed, $F(1,118) < .001$, $p > .5$, $\eta_p^2 < .001$, with overall response accuracy rates equivalent for monolinguals ($M = 92.8\%$, $SE = 0.7$) and bilinguals ($M = 92.8\%$, $SE = 0.7$). In addition, an interaction between condition and task emerged, confirming differences in interference resolution across the two tasks. With the added neutral condition, this interaction was consistent with predicted differences in facilitation and inhibition across the Stroop and Simon tasks, $F(1,118) = 64.0$, $p < .001$, $\eta_p^2 = .4$. Consistent with Experiment 1, there was also a two-way interaction between task and group, $F(1,118) = 5.0$, $p < .05$, $\eta_p^2 = .04$, suggesting differences in Stroop vs. Simon performance across the two groups. However, in contrast to Experiment 1, no three-way interaction between trial type, task, and group was found, $F(1,118) = 1.5$, $p > .1$, $\eta_p^2 = .01$. Follow-up t -tests to examine the interaction between task and group yielded larger differences between tasks for bilinguals ($M_{Simon-Stroop} = 4.7\%$, $SE = 0.6$) than for monolinguals ($M_{Simon-Stroop} = 2.2\%$, $SE = 1.0$), $t(118) = 2.2$, $p < .05$. Follow-up 2×2 ANOVAs were conducted to examine the interaction between condition and task. When neutral and *incongruent* conditions were entered into the analysis, no interaction was found between condition and task, $F(1,118) = 0.6$, $p > .1$, $\eta_p^2 = .005$, suggesting that the Stroop and Simon tasks yielded similar *inhibition* effects. However, when neutral and *congruent* conditions were entered into the analysis, an interaction was identified between condition and task, $F(1,118) = 55.4$, $p < .001$, $\eta_p^2 = .3$, suggesting differences in Stroop and Simon *facilitation*. Follow-up t -tests suggested that significant facilitation effects were present for both Stroop ($t(119) = 3.6$, $p < .001$) and Simon tasks ($t(119) = 9.0$, $p < .001$), with smaller effects on the Stroop task ($M = 1.01\%$, $SE = 0.3$) than on the Simon task ($M = 6.3\%$, $SE = 0.7$), $t(119) = 7.4$, $p < .001$.

Response latencies—When response latencies were entered into the $3 \times 2 \times 2$ mixed ANOVA, results confirmed a main effect of trial type, $F(1,118) = 943.0, p < .0001, \eta_p^2 = .9$, suggesting that participants were overall slower on incongruent trials ($M = 523.6$ ms, $SE = 5.7$) than on neutral trials ($M = 478.9$, $SE = 5.3$) or on congruent trials ($M = 439.0$ ms, $SE = 4.9$). In addition, as in Experiment 1, a main effect of task, $F(1,118) = 71.7, p < .001, \eta_p^2 = .4$, showed that response times were faster on the Stroop task ($M = 461.2$ ms, $SE = 5.8$) than on the Simon task ($M = 499.8$ ms, $SE = 5.4$), while no main effect of group was observed (monolinguals: $M = 473.3$ ms, $SE = 7.3$; bilinguals: $M = 487.7$ ms, $SE = 7.3$), $F(1,118) = 2.0, p > .1, \eta_p^2 = .02$. Critically, two-way interactions were found between task and group, $F(1,118) = 6.9, p = .01, \eta_p^2 = .1$, and between task and condition, $F(1,118) = 51.0, p < .001, \eta_p^2 = .3$, identifying group differences in overall reaction times on Stroop and Simon tasks that had not emerged in Experiment 1, as well as task differences in inhibition and facilitation components. The three-way interaction between competitor, task, and group remained insignificant, $F(1,118) = 1.1, p > .1, \eta_p^2 = .01$. Follow-up t -tests to examine the task \times group interaction replicated the pattern of findings identified in the accuracy analyses of Experiment 1, with bilinguals showing a bigger difference between Stroop and Simon performance ($M_{Simon-Stroop} = 50.5$ ms, $SE = 7.0$) than the monolinguals ($M_{Simon-Stroop} = 26.6$ ms, $SE = 5.8$), $t(118) = 2.6, p = .01$. Follow-up t -tests to examine the task \times condition interaction suggested that the Stroop task yielded larger inhibition effects ($M = -55.5$ ms, $SE = 2.7$) than the Simon task ($M = -33.9$ ms, $SE = 2.6$), $t(119) = 7.2, p < .001$, but smaller facilitation effects ($M = 29.7$ ms, $SE = 1.9$) than the Simon task ($M = 50.1$ ms, $SE = 2.6$), $t(119) = 8.0, p < .001$.

Efficiency scores—As in Experiment 1, accuracy and reaction time data were combined in efficiency scores to adjust for speed–accuracy trade-offs (see Figure 3). Consistent with Experiment 1 findings, main effects of trial ($F(1,118) = 346.1, p < .001, \eta_p^2 = .8$) and task ($F(1,118) = 69.7, p < .001, \eta_p^2 = .4$) emerged, together with the critical two-way interactions between task and group ($F(1,118) = 9.4, p < .01, \eta_p^2 = .1$) and between task and condition ($F(1,118) = 58.7, p < .001, \eta_p^2 = .3$). In contrast to Experiment 1 findings, the three-way interaction between trial, task, and group did not reach significance, $F(1,118) = 2.1, p > .1, \eta_p^2 = .02$.

Follow-up t -tests to examine the task \times group interaction confirmed that differences between Stroop and Simon efficiency scores were larger for bilinguals ($M_{Simon-Stroop} = 86.8$ ms/proportion correct, $SE = 10.4$) than for monolinguals ($M_{Simon-Stroop} = 40.2$ ms/proportion correct, $SE = 11.1$), $t(118) = 3.1, p < .01$, replicating findings of a greater performance advantage on the Stroop task relative to the Simon task in bilinguals (Stroop: $M = 492.3$ ms/proportion correct, $SE = 7.1$; Simon: $M = 579.1$ ms/proportion correct, $SE = 9.7$) compared to monolinguals (Stroop: $M = 503.8$ ms/proportion correct, $SE = 17.5$; Simon: $M = 544.0$ ms/proportion correct, $SE = 13.7$). Follow-up t -tests to examine the task \times condition interaction suggested that the Stroop ($M = -120.1$ ms/proportion correct, $SE = 8.6$) and Simon tasks ($M = -104.4$ ms/proportion correct, $SE = 11.0$) yielded similar inhibition effects, $t(119) = 1.5, p > .1$, with smaller facilitation effects on the Stroop task ($M = 36.6$ ms/proportion correct, $SE = 3.2$) than on the Simon task ($M = 93.5$ ms/proportion correct, $SE = 6.0$), $t(119) = 9.7, p < .001$.

Discussion

In Experiment 2, a larger group of bilinguals and monolinguals was recruited to replicate Experiment 1 findings of enhanced bilingual Stroop vs. Simon performance. Participants in Experiment 2 ($M = 481.3$, $SE = 4.9$) performed overall slower than participants in Experiment 1 ($M = 422.1$, $SE = 7.0$), $F(1,176) = 48.2$, $p < .001$, $\eta_p^2 = .2$, with comparable accuracy rates across Experiment 2 ($M = 92.0$, $SE = 0.5$) and Experiment 1 ($M = 90.7$, $SE = 0.7$), $F(1,176) = 1.8$, $p > .1$, $\eta_p^2 = .01$. Therefore, efficiency scores provide the best comparison across the two cohorts in order to avoid group differences in speed–accuracy tradeoffs. In both experiments, an interaction between group and task suggested that bilinguals showed better overall Stroop performance relative to Simon performance. In the monolingual groups, Stroop–Simon differences were either non-existent (Experiment 1) or significantly smaller than in bilinguals (Experiment 2).

In Experiment 1 a three-way interaction between task, trial type and group was identified, and follow-up tests yielded a smaller Stroop effect for bilinguals than for monolinguals. In Experiment 2, the three-way interaction between task, trial type and group did not reach significance, suggesting similar inhibition processes across groups. Therefore, findings from the two experiments suggest that while bilingual–monolingual absolute differences in inhibition are variable across young populations, stable group differences are consistently found in the relationship between Stroop and Simon performance. In addition, Experiment 2 confirmed previous findings by Van Heuven et al. (2011) that the magnitude of the Stroop inhibition effect is bigger than the magnitude of the Stroop facilitation effect. The finding of comparable Simon inhibition and facilitation effects is also consistent with previous research (e.g., Lu & Proctor, 1995). For the specific spatial Stroop and Simon tasks employed in Experiments 1 and 2, these findings suggest that the inhibition component accounts for 77% of the Stroop effect and 53% of the Simon effect. It is therefore likely that the smaller bilingual Stroop effect observed in Experiment 1 was driven by bilingual–monolingual differences in Stroop inhibition. In sum, the shared finding across both studies is that bilinguals showed better Stroop performance relative to Simon performance, while monolinguals showed no differences or smaller differences between the two tasks. To identify findings that generalize across both bilingual groups, an overall analysis was conducted across the two data sets.

Comparisons across Experiments 1 and 2—To establish the consistency of patterns obtained across the two participant samples, findings for efficiency scores are reported for all participants combined on the congruent and incongruent conditions of the Stroop and Simon tasks (see Figure 4). Across all bilinguals and monolinguals, a main effect of trial type, $F(1,176) = 463.4$, $p < .001$, $\eta_p^2 = .7$, and a main effect of task, $F(1,176) = 35.2$, $p < .001$, $\eta_p^2 = .2$, were confirmed. No main effect of group was observed, $F(1,176) = 0.1$, $p > .5$, $\eta_p^2 = .001$, suggesting similar overall efficiency scores across monolinguals and bilinguals. However, the critical two-way interaction between task (Stroop, Simon) and group, $F(1,176) = 12.0$, $p = .001$, $\eta_p^2 = .1$, as well as a three-way interaction between task, trial type, and group, $F(1,176) = 8.7$, $p < .01$, $\eta_p^2 = .1$, were observed. To examine the interaction between task and group, overall Simon vs. Stroop efficiency scores were compared across bilinguals and monolinguals, and findings confirmed that performance

differences on the Stroop vs. the Simon task were significantly bigger for bilinguals ($M_{Simon-Stroop} = 70.3$ ms/proportion correct, $SE = 9.8$) than for monolinguals ($M_{Simon-Stroop} = 21.2$ ms/proportion correct, $SE = 9.6$), $t(178) = 3.6$, $p < .001$.

To examine the three-way interaction between trial type, task and group, separate ANOVAs were conducted for bilinguals and monolinguals. In bilinguals, a main effect of task confirmed better performance on the Stroop task ($M = 488.8$ ms/proportion correct, $SE = 7.2$) than on the Simon task ($M = 559.1$ ms/proportion correct, $SE = 9.8$), $F(1,89) = 51.5$, $p < .001$, $\eta_p^2 = .4$. In addition, an interaction between trial type and task was identified, $F(1,89) = 16.7$, $p < .001$, $\eta_p^2 = .2$, with the Stroop effect ($M_{Congruent-Incongruent} = -157.4$ ms/proportion correct, $SE = 9.1$) smaller than the Simon effect ($M_{Congruent-Incongruent} = -223.6$ ms/proportion correct, $SE = 16.9$), $t(89) = 4.1$, $p < .001$. The monolinguals also showed a main effect of task ($M_{Stroop} = 505.3$, $SE = 13.8$; $M_{Simon} = 527.2$, $SE = 10.8$), $F(1,89) = 5.1$, $p < .05$, $\eta_p^2 = .1$, but did NOT show an interaction between condition and task, $F(1,89) = 1.4$, $p > .1$, $\eta_p^2 = .02$, suggesting that they performed more similarly across the Stroop and Simon tasks, with no task differences in conflict resolution. Together, findings confirm that bilinguals show a relative advantage for overall Stroop vs. Simon performance for Stroop-type inhibition compared to Simon performance, while monolinguals show more similar conflict resolution patterns across these two tasks.

General discussion

The aim of the current study was to examine the relative sensitivity of perceptual-level (Stimulus–Stimulus) and response-level (Stimulus–Response) inhibition mechanisms to bilingual experience. Under the hypothesis that bilingual experience acts on specific inhibition mechanisms, performance of young bilinguals and monolinguals was compared on a nonlinguistic Stroop task and a nonlinguistic Simon task. It was expected that if, through cross-linguistic competition, Stimulus–Stimulus inhibition of lexical information were particularly sensitive to bilingual experience, then bilinguals would be more likely to show an advantage on inhibition tasks that also call for conflict resolution of two conflicting stimulus dimensions. The results were consistent with this prediction: In bilinguals, a specific advantage was found on performance during the nonlinguistic Stroop task relative to the Simon task. In contrast, monolinguals performed more similarly across the two tasks. The finding of better bilingual Stroop performance relative to bilingual Simon performance suggests that bilingualism may be particularly likely to modulate cognitive control mechanisms that are dedicated to resolving Stimulus–Stimulus competition between two dimensions of the same stimulus.

In the combined sample of bilinguals in Experiment 1 and 2, a Stroop–Simon dissociation in overall performance was identified, with more efficient Stroop performance, and with a smaller Stroop than Simon effect, relative to monolinguals who showed less marked differences between Stroop and Simon tasks. In addition, Experiment 1 yielded a bilingual Stroop inhibition advantage over monolinguals. The current set of experiments suggests that, across diverse groups of young bilinguals and their monolingual peers, Stroop and Simon performance are significantly more differentiated in bilinguals than monolinguals, a stable finding that can co-occur with subtle bilingual Stroop advantages relative to monolinguals

(Experiment 1). It is likely that the nature of bilingual Stroop advantages, relative to monolinguals, is somewhat variable given that all individuals in this age group are peak performers, and given subtle overall differences across populations. Examination of WITHIN-GROUP PATTERNS across tasks, and comparison of such patterns between groups, may better reflect the influence of bilingualism on specific cognitive mechanisms, because each participant effectively acts as their own baseline (see Paradis, 2011, for a similar approach to the assessment of bilinguals). In sum, we can conclude that, within the bilingual cognitive system, and across bilinguals with different backgrounds, Stroop-type mechanisms are privileged over conflict resolution mechanisms that underlie Simon performance.

One factor that may drive the robustness of Stroop–Simon dissociations, and may have contributed to the observed differences between Experiment 1 and 2, is code-switching and the differences in previous code-switching experience across the two samples of bilinguals. During code-switching, bilinguals are likely to communicate most efficiently if lexical representations are active in both languages, because output may be produced in either language and input may be received in either language. With lexical activation of both languages relevant for communication, Stimulus–Stimulus inhibition may be recruited less since there is less need to inhibit cross-linguistic lexical activation. During production, the response language may be selected at the output level and irrelevant responses may be inhibited via Stimulus–Response inhibition (Linck et al., 2012; Marian, Blumenfeld, Mizrahi, Kania & Cordes, 2013). During comprehension, cross-linguistic word candidates may be considered longer in both languages if code-switches are expected, also potentially reducing the need for efficient lexical-level Stimulus–Stimulus inhibition. In contrast to the code-switching scenario, during unilingual processing bilinguals are likely to communicate most efficiently if co-activation of the irrelevant language is muted as soon as it occurs. As a result, Stimulus–Stimulus inhibition can consistently operate at the lexical level to reduce cross-linguistic co-activation of the irrelevant language (e.g., Shook & Marian, 2013). Following this logic, fewer opportunities may be present for lexical Stimulus–Stimulus inhibition if bilinguals are immersed in code-switching environments. The bilinguals in Experiment 2 were native Spanish-speakers from Southern California, who spent more time in Spanish-speaking environments (35%) than the Midwestern native English-speaking bilinguals in Experiment 1 (21%). The bilinguals in Experiment 2 may have been more exposed to code-switching as a result of more balanced language exposure and inter-generational differences in language preferences that are frequently present in families of Spanish heritage speakers (e.g., Ortman & Stevens, 2008). Therefore, it is possible that one of the reasons why the bilinguals in Experiment 2 did not show as large a difference between Stroop and Simon inhibition is because their linguistic background may include more experience with code-switching than that of bilinguals in Experiment 1 (but note that Stimulus–Stimulus performance was still stronger than Stimulus–Response performance, even in this population, supporting the hypothesis that Stimulus–Stimulus conflict is generally more common within the bilingual system). Thus, the nature of bilingual experience may influence the type of bilingual advantage present (e.g., Tao, Marzecová, Taft, Asanowicz & Wodniecka, 2011). Future research can further examine the relationship between specific aspects of bilingual experience and inhibitory control.

The main finding of enhanced Stroop vs. Simon performance in young bilinguals is consistent with the observation that Stroop advantages are more commonly reported than Simon advantages in this age-group (e.g., Costa et al., 2008; Hernández et al., 2010; Luk et al., 2011; see Tables 1 and 2). On Stroop tasks, previous studies identified both speed advantages (Bialystok, 2006; Bialystok & De Pape, 2009; Costa et al., 2008; Costa et al., 2009; Hernández et al., 2010) and conflict resolution advantages (Bialystok et al., 2008; Costa et al., 2008; Costa et al., 2009; Hernández et al., 2010; Luk et al., 2011). In contrast, studies examining bilingual Simon advantages have not found advantages in young adults (Bialystok, 2006; Bialystok, Martin & Viswanathan, 2005; Salvatierra & Rosselli, 2011) but have found advantages in other age groups (Bialystok, Martin & Viswanathan, 2005: children, 30–59-year-olds, 60–80-year-olds; Bialystok et al., 2004: mean age = 43 years, 72 years; Salvatierra & Rosselli, 2011: mean age = 61 years; Schroeder & Marian, 2012: mean age = 81 years). Bialystok (2006) tested the same group of undergraduate participants on both an arrow-based Stroop inhibition task similar to the one in the current study and a classic Simon task, with blue or red shapes appearing on either the right side or the left side of the display. Bialystok (2006) identified a bilingual advantage only on the most difficult condition of the Stroop arrow-task, a finding that was ascribed to overall task difficulty as well as to greater perceptual conflict on the arrows task, consistent with the current findings. Interestingly, while bilingual advantages have previously been identified on more challenging tasks (e.g., Bialystok, 2006), the current findings show a relative advantage for bilinguals on the task that was LESS challenging for both groups. This finding suggests that a mechanistic explanation rather than a task-difficulty explanation may be more appropriate for the current data. In sum, our findings align well with previous research that has been more likely to reveal honed Stroop than Simon performance in young bilingual adults, and the emerging pattern can be explained within the framework of the Dimensional Overlap model, with distinct loci and roles for Stimulus–Stimulus and Stimulus–Response inhibition.

While a recent meta-analysis suggests that Stroop advantages are not always present in young adult bilinguals (Hilchey & Klein, 2011), findings from the current study suggest that, even in the absence of clear bilingual–monolingual advantages, cognitive effects of bilingualism can be observed by comparing relative performance across cognitive control tasks. Bilingual–monolingual differences in the relationship between separable inhibitory control mechanisms provide an important source of information on how bilingual experience shapes the cognitive system. This is especially the case in young adult peak performers where absolute bilingual advantages are more elusive but important cognitive differences may nevertheless be present. Hilchey and Klein (2011) also note that absolute speed advantages may be found in addition or instead of inhibition advantages. Absolute speed advantages have been attributed to enhanced skills in conflict monitoring (Costa et al., 2008). A number of studies have identified overall speed advantages on Stroop-type tasks (e.g., Bialystok, 2006; Bialystok & De Pape, 2009; Emmorey, Luk, Pyers & Bialystok, 2008; Hernández et al., 2010). Our main finding of bilinguals' overall smaller efficiency scores (i.e., quicker and more accurate performance) on the Stroop relative to the Simon task falls within the same category of enhanced monitoring skills, and suggests that bilinguals may be particularly sensitive to Stimulus–Stimulus conflict. These findings can be conceptualized within the Dimensional Overlap Model where Stroop tasks (but not Simon

tasks) are characterized by perceptual overlap between stimulus dimensions. It is possible that honed performance on Stroop relative to Simon tasks is present because bilinguals experience a higher amount of Stimulus–Stimulus conflict across a number of language processing contexts (comprehension and production), resulting in a bigger training ground for Stroop-type competition resolution.

Across the two experiments, Stroop effects emerged from different aspects of bilinguals' responses. Specifically, while effects were present in both experiments for efficiency scores, they were driven primarily by accuracy rates in Experiment 1 and by reaction times in Experiment 2. It is possible that Experiment 1 yielded a bilingual effect on response accuracies because the ratio of congruent to incongruent trials was high (3:1), resulting in a high potential for errors if participants did not monitor responses closely (e.g., West & Alain, 2000). In Experiment 2, the ratio of congruent to other (neutral and incongruent) trials was 3:2, perhaps reducing strong expectancies for congruent trials, resulting in slower performance and pushing effects from response accuracies into latencies. Another reason for the accuracy effects may be faster reaction times in Experiment 1 (around 420 ms on the Stroop task) while reaction times in Experiment 2 (around 489 ms on the Stroop task) were aligned more closely with previous studies (473–550 ms in Bialystok, 2006; Bialystok et al., 2008; Bialystok & De Pape, 2009). Participants' faster responses in Experiment 1 may have resulted in speed–accuracy trade-offs, yielding the accuracy effects across tasks and groups. Notably, efficiency scores, which were calculated to account for potential speed–accuracy tradeoffs, confirmed differences between Stroop and Simon effects in the bilingual but not the monolingual group across both experiments. In sum, despite differences between studies, findings suggest that bilinguals are more efficient at inhibiting irrelevant information and identifying correct responses on the Stroop task than the Simon task.

Evidence from bimodal vs. unimodal bilinguals converges with the hypothesis that same-modality perceptual conflict may enhance lexical competition and underlie some bilingual advantages. Emmorey et al. (2008) compared inhibition performance in unimodal bilinguals (speakers of English as well as Cantonese, Italian, or Vietnamese) and bimodal bilinguals (users of English and American Sign Language) on a flanker task. Emmorey et al. found that, relative to a monolingual control group, only unimodal bilinguals showed an inhibition advantage. While parallel activation of ASL has been observed during English word recognition in bimodal bilinguals (e.g., Shook & Marian, 2012), and Stimulus–Stimulus inhibition is recruited to resolve such cross-linguistic competition (Giezen, Blumenfeld, Shook, Marian & Emmorey, 2013), such inhibition mechanisms may be less engaged in bimodal than unimodal bilinguals. Emmorey et al. argued that a bilingual advantage likely arises from the fact that two language systems interact and interfere within the SAME MODALITY (Emmorey, Borinstein, Thompson & Gollan, 2008; Pyers & Emmorey, 2008), necessitating more consistent application of Stimulus–Stimulus inhibition.

The current finding that Stroop and Simon tasks are differentially influenced by bilingual experience is also consistent with neuroimaging studies showing that Stroop and Simon tasks have different loci of inhibition. Liu et al. (2004) compared neural correlates of inhibition on a Stroop and a Simon task similar to the tasks employed in the current experiment. Findings showed activation patterns in the inferior parietal cortex that were

unique to Stroop-type inhibition. Crucially, the current pattern of findings is consistent with Luk, Anderson, Craik, Grady & Bialystok (2010) who showed that monolinguals and bilinguals activated different neural networks during interference control on a flanker (Stimulus–Stimulus inhibition) task but showed similar activation patterns on a go no-go task (Stimulus–Response inhibition) task. When Luk et al. correlated performance on the flanker task with neural activation, they found that bilinguals (but not monolinguals) who performed better on the flanker task also showed greater activation in a network of areas that have been implicated in bilingual language control (Abutalebi, 2008). These findings are consistent with the conclusion that shared mechanisms may underlie Stroop-type and linguistic processing and that Stroop-type inhibition may be particularly sensitive to bilingualism.

While the current experiments highlight one aspect of cognitive control that may be particularly sensitive to bilingual experience – perceptual-level Stimulus–Stimulus inhibition – other cognitive control mechanisms are likely to yield bilingual advantages (e.g., Colzato, Bajo, van den Wildenberg & Paolieri, 2008; Treccani, Argyri, Sorace & Della Sala, 2009). For example, a number of studies suggest bilingual advantages on task-switching (Bialystok, 1999; Bialystok & Martin, 2004; Kovács & Mehler, 2009; Prior & MacWhinney, 2010). Such tasks may have Stimulus–Stimulus components (e.g., on the Dimensional Card Sort task, the perceptual salience of SHAPE must be suppressed when the rule to sort according to shape no longer applies, Bialystok, 1999). However, task-switching, which may be honed by bilinguals' need to switch languages (e.g., Festman, Rodriguez-Fornells & Münte, 2010), likely relies on Stimulus–Response inhibition (e.g., Linck et al., 2012). Together with findings of Simon advantages in older bilinguals (Bialystok et al., 2004), these results suggest that Simon-type inhibition may also be related to bilingual processing but in a manner that may be constrained to linguistic contexts different from contexts associated with Stroop-type inhibition. Relatedly, both tasks in the present study contained Simon-components, with two possible Stimulus–Response mappings (in addition to Stimulus–Stimulus overlap on the Stroop task). It is possible that, while Stimulus–Response competition on its own did not yield processing advantages in bilinguals, Stimulus–Stimulus competition in combination with Stimulus–Response competition created advantages. In fact, other Stroop-type tasks (the classic Stroop task, the flanker task, etc.) contain a Stimulus–Response competition element. Since Stroop performance was generally better in the current study, it is unlikely that multiple levels of conflict (Stimulus–Stimulus AND Stimulus–Response) increased difficulty and yielded processing advantages in bilinguals because of greater cognitive demands. Whether Stimulus–Stimulus competition on its own or in combination with Stimulus–Response competition yields advantages can be examined in future research.

In sum, current findings suggest that an increased need to inhibit perceptually-ambiguous information (including cross-linguistic lexical alternatives), may play a key role in driving bilingual Stimulus–Stimulus inhibition performance. Different findings for Stroop and Simon tasks are likely due to differences in the loci of inhibition: While interference on the Simon task is created by incongruent mappings between stimulus and response (e.g., an upward-facing arrow on the right side of the screen requiring a left key-press), interference on the Stroop tasks is created by incongruent information within the stimulus (e.g., a right-

facing arrow on the left side of the screen, e.g., Liu et al., 2004). The current findings provide a direct comparison between Stroop and Simon tasks in bilinguals, and point to specific task components (as specified by the Dimensional Overlap Model; Kornblum, 1994) that may be most influenced by bilingual experience. It is likely that comparisons of cognitive control tasks with varying loci of interference will be instrumental in unifying diverse findings of bilingual performance and language–cognition interactions.

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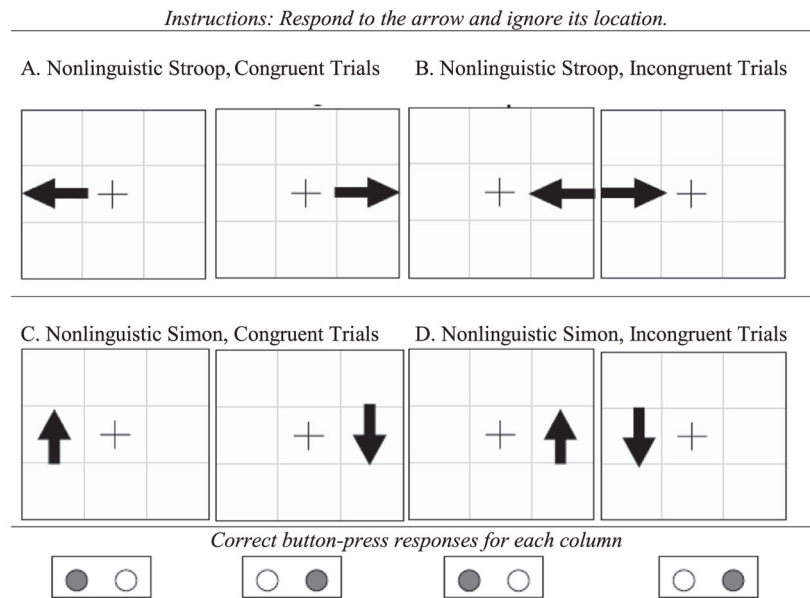
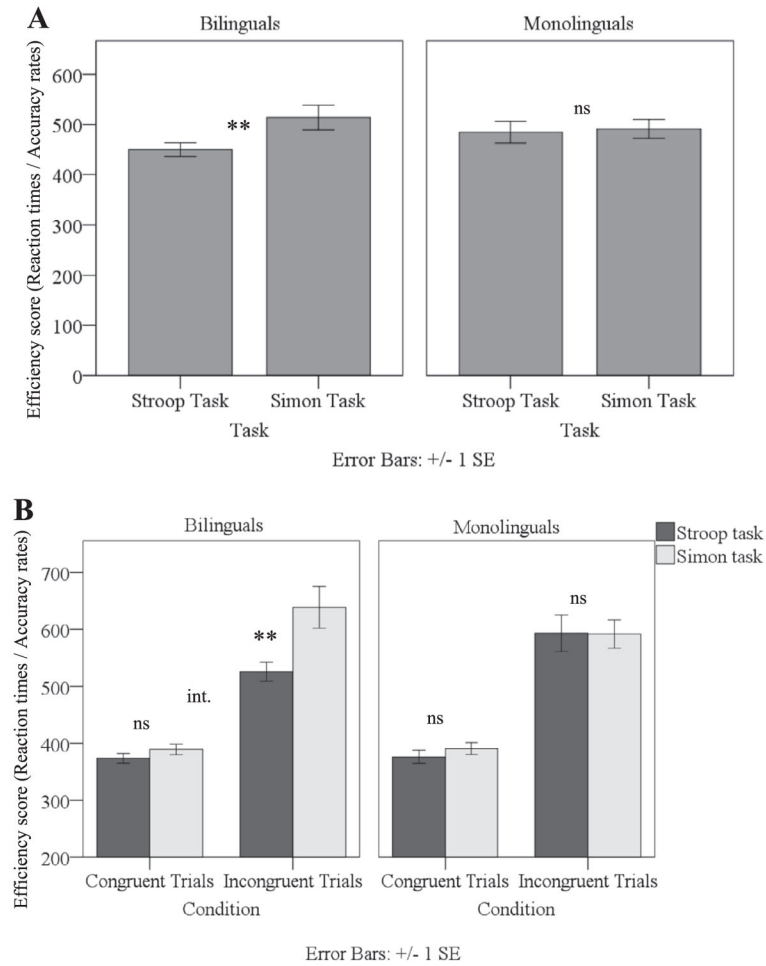


Figure 1. Illustration of the cognitive inhibition tasks. Panels A and B show the nonlinguistic Stroop task (congruent conditions and incongruent Stimulus–Stimulus conflict conditions, respectively). Panels C and D show the nonlinguistic Simon task (congruent conditions and incongruent Stimulus–Response conflict conditions, respectively). Correct responses (right button or left button) are shown at the bottom of each column.

**Figure 2.**

Experiment 1. Performance efficiency (reaction times divided by accuracy rates) on the nonlinguistic Stroop task, as compared to the nonlinguistic Simon task. A: Overall performance on nonlinguistic Stroop and Simon tasks. B: Performance on congruent and incongruent trials across tasks, ** $p < .001$, ns = not significant; int. = task \times condition interaction.

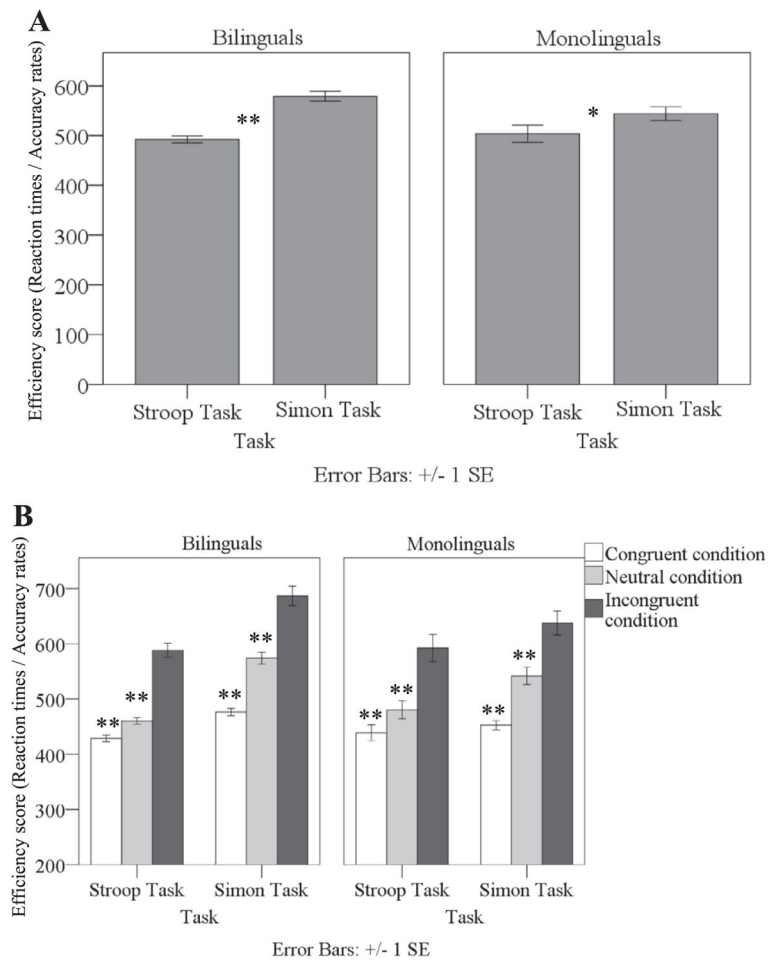
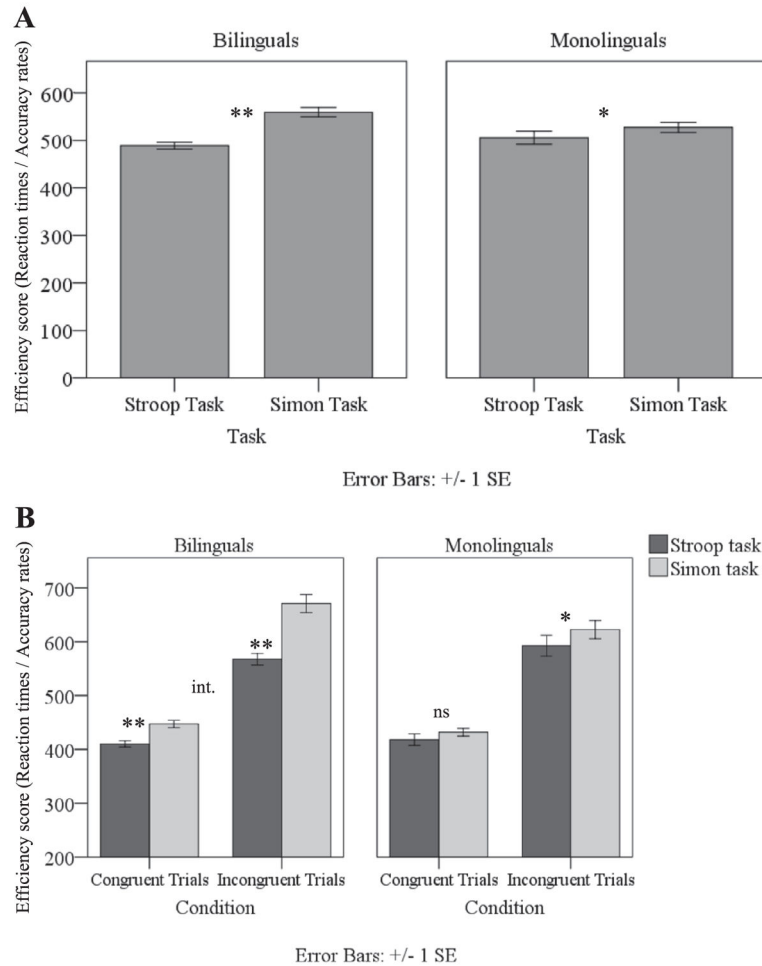


Figure 3. Experiment 2. Performance efficiency (reaction times divided by accuracy rates) on the nonlinguistic Stroop task, as compared to the nonlinguistic Simon task. A: Overall performance on nonlinguistic Stroop and Simon tasks. B: Performance on congruent, neutral, and incongruent trials across tasks, * $p < .01$, ** $p < .001$.

**Figure 4.**

Experiments 1 and 2 combined. Performance efficiency (reaction times divided by accuracy rates) for all participants combined (90 bilinguals and 90 monolinguals). A: Overall performance on nonlinguistic Stroop and Simon tasks. B: Performance on congruent and incongruent trials across tasks, * $p < .05$, ** $p < .001$; ns = not significant; int. = task \times condition interaction.

Table 1

Stimulus–Stimulus Conflict: Stroop Task. Overview of studies where (A) no bilingual Stroop advantage was identified, where (B) a bilingual Stroop inhibition advantage was identified, or (C) where a bilingual overall speed advantage was identified on the Stroop task. Stimulus–Stimulus inhibition tasks include Stroop spatial arrows, Stroop color-word, Stroop number, and flanker tasks. When only specific groups or experiments show an effect, they are listed next to the relevant check mark.

Study	A. No bilingual advantages	B. Bilingual inhibition advantages	C. Bilingual speed advantages
<i>Stroop (spatial arrows) task</i>			
1. Bialystok, 2006 ¹ (n = 97, 22yo)	20.2yo	67.8yo	
2. Bialystok et al., 2008 ¹ (n = 96, 20.2yo, 67.8yo)			
3. Bialystok & DePape, 2009 ¹ (n = 48, 23.8yo)			
4. Martin-Rhee & Bialystok, 2008 ¹ (Expt 3: n = 32, 8yo)			
<i>Stroop (color-word) task</i>			
1. Bialystok et al., 2008 (n = 96, 20.2yo, 67.8yo)		high-proficient bilinguals	high-proficient bilinguals
2. Singh & Mishra, 2012 (n = 68, 22.3yo), high- and low-proficiency bilinguals ²			
<i>Stroop (number) task</i>			
1. Hernández et al., 2010 (Expt 1: n = 82, 21.2yo)			
<i>Flanker task</i>			
1. Carlson & Meltzoff, 2008 ³ (n = 50, 6yo)	Expt 1 bimodal bilinguals	Expt 2	Expt 2 unimodal bilinguals early bilinguals
2. Costa et al., 2008 (n = 200, 22yo)			
3. Costa et al., 2009 (Expt 1: n = 120, 20.1yo; Expt 2: n = 124, 20.4yo)			
4. Emmorey et al., 2008 (n = 45, 47.8yo), unimodal and bimodal bilinguals			
5. Luk et al., 2011 (n = 157, 21.1yo)			
6. Tao et al., 2011 (n = 100, 20yo), early and late bilinguals			

yo = years old

¹ Even though effects are reported as Simon effects, they are categorized here as Stroop-like effects because perceptual conflict also exists within the same stimulus (e.g., a RIGHT-pointing arrow presented on the LEFT side of the display), also see footnote 1. Bialystok (2006): Speed-advantages were found only in a high-switch condition.

²High-proficiency bilinguals were compared to low-proficiency bilinguals and there was no monolingual control group. In all other studies reported in Table 1, monolingual reference groups were present.

³No analyses reported to evaluate bilingual advantage on the flanker task, but a composite conflict resolution advantage emerged across tasks.

Table 2

Stimulus–Response Conflict: Simon Task. Overview of studies where (A) no bilingual Simon advantage was identified, where (B) a bilingual Simon inhibition advantage was identified, or (C) where a bilingual overall speed advantage was identified on the Simon task. When only specific groups or experiments show an effect, they are listed next to the relevant check mark.

Study	A. No bilingual advantages	B. Bilingual inhibition advantages	C. Bilingual speed advantages
1. Bialystok, 2006 (n = 97, 22yo)			
2. Bialystok, Craik, Grady et al., 2005 (n = 29, 29yo, 10 French–English bilinguals, 9 Cantonese–English bilinguals)	French–English bilinguals		Cantonese–English bilinguals
3. Bialystok et al., 2004 (Expt 1: n = 40, 43yo, 71.9yo; Expt 2: n = 94, 42.6yo, 70.3yo)			
4. Bialystok, Martin & Viswanathan, 2005 (Expt 1: n = 34, children; Expt 2: n = 40, children; Expt 3: n = 96, 20–30yo; Expt 4: n = 40, 30–59yo, 60–80yo; Expt 5: n = 94, 30–59yo, 60–80yo)	Expt 3		Expt 1, 2, 4, 5
5. Martin-Rhee & Bialystok, 2008 (Expt 1: n = 34, 4.8yo; Expt 2: n = 41, 4.5yo)			
6. Morton & Harper, 2007 (n = 34, 6.9yo)			
7. Salvatierra & Rosselli, 2011 (n = 233, 26.8yo, 64.1yo)	26.8yo	64.1yo	
8. Schroeder & Marian, 2012 (n = 36, 80.8yo)			

yo = years old

Table 3

Comparison between bilingual participants in Experiments 1 and 2.

	Experiment 1 Mean (SE)	Experiment 2 Mean (SE)	<i>t</i> -test
Age	22.0 (0.9)	21.7 (0.4)	$t(88) = 0.3, p > .1$
Age of Spanish acquisition	2.9 (0.7)	1.0 (.2)	$t(88) = 3.5, p = .001$
Age fluent in Spanish	8.8 (1.2)	4.4 (0.4)	$t(88) = 4.3, p = .001$
Age of English acquisition	1.4 (0.3)	4.4 (0.4)	$t(88) = 5.3, p < .001$
Age fluent in English	4.9 (0.6)	7.0 (0.4)	$t(88) = 2.9, p < .01$
Years of bilingual experience ¹	18.2 (1.1)	17.1 (0.5)	$t(88) = 1.1, p > .1$
Years of functional bilingualism ²	12.2 (1.2)	13.8 (0.6)	$t(88) = 1.4, p > .1$
Self-reported English proficiency	9.4 (0.1)	9.4 (0.1)	$t(88) = 0.6, p > .1$
Self-reported Spanish proficiency	7.7 (0.2)	8.5 (0.2)	$t(88) = 3.0, p < .01$
Spanish receptive vocabulary (TVIP, raw scores)	111.4 (1.3)	107.4 (1.1)	$t(88) = 2.5, p < .05$
English receptive vocabulary (PPVT, raw scores)	187.5 (1.6)	176.3 (1.1)	$t(88) = 5.9, p < .001$
Percentage of Spanish exposure	20.5 (2.4)	35.0 (2.2)	$t(88) = 4.1, p < .001$

¹Years of bilingual experience = age at testing minus age when participants started acquiring their second language.

²Years of functional bilingualism = age at testing minus the age when participants reported fluency in the language that became fluent last.