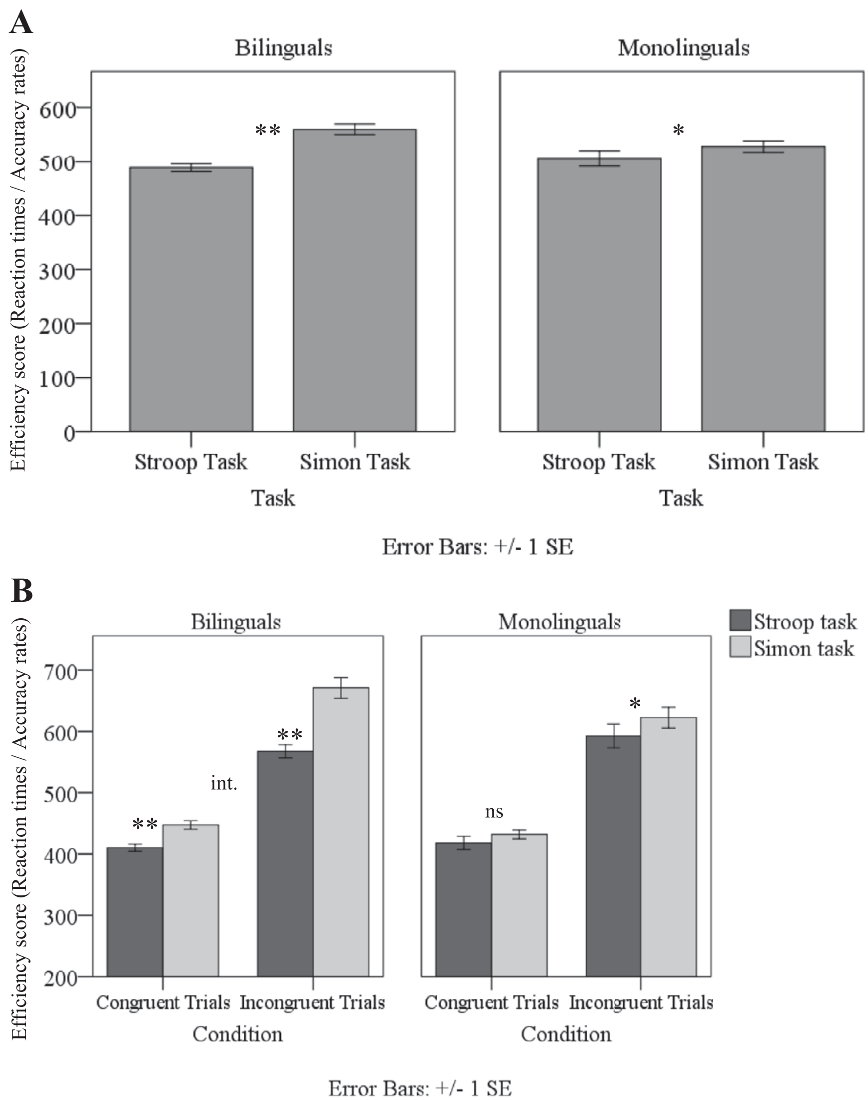

Figure 4. Experiments 1 and 2 combined. Performance efficiency (reaction times divided by accuracy rates) for all participants combined (90 bilinguals and 90 monolinguals). A: Overall performance on nonlinguistic Stroop and Simon tasks. B: Performance on congruent and incongruent trials across tasks, $^{*}p < .05$, $^{**}p < .001$; ns = not significant; int. = task × condition interaction.

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 trade-offs, 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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