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The elusive link between language control and executive control: A case of limited transfer

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The elusive link between language control and executive control: A case of limited transfer

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We investigated the relationship between language control and executive control by testing three groups of bilinguals (104 participants) and 54 monolinguals in a training and transfer paradigm. Participants practised either a language or a non-linguistic colour/shape switching task and were tested one week later on both tasks. The colour/shape task produced significant immediate improvement with training, which was maintained one week later, but exhibited no cross-task transfer effects. In the dominant language, training effects did not persist after one week, and there were no transfer effects. In the non-dominant language there were significant training effects that lasted one week, and there was also transfer facilitation from prior practice with the colour/shape task, which was limited to a reduction in *mixing* costs. Despite limited transfer, there were significant correlations between tasks in mixing costs for bilinguals, in switching costs for monolinguals, and in intrusion errors for all participants. Finally, the pattern of costs observed for the two tasks exhibited both similarities and differences across participants. These results imply a limited but significant role for executive control in bilingual language control, possibly playing a stronger role in facilitating non-dominant-language production and in supporting the ability to monitor response outcomes to avoid errors.

Keywords: Bilingualism; Cognitive control; Task switching; Language switching.

People who regularly speak two languages engage in a range of behaviours and thought processes that monolinguals do not use. These include deciding which language to speak with whom, when to switch languages, when to engage in language mixing, and perhaps even constantly monitoring which language is being spoken at any given time. With continued bilingual language use it might seem that these abilities could develop as specialised skills within the language domain without influencing cognitive functions outside of the language system. However, a rapidly accumulating body of experimental evidence suggests that bilingualism confers benefits for a range of non-linguistic cognitive skills often described under the broad term ‘‘executive functions’’ (Bialystok, Craik, & Luk, 2012; Costa, Hernández, & Sebastián-Gallés, 2008; Prior & Gollan, 2011). Findings of executive function benefits for bilinguals imply transfer from linguistic skills to non-linguistic tasks with shared processing requirements.

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Bilingual advantages in executive functions have been reported throughout the lifespan from infancy (Kovács, 2009; Kovács & Mehler, 2009) to older age, (Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Luk, 2008; Bialystok, Craik, & Ryan, 2006), in direct measures of behaviour (e.g., faster response times, Costa et al., 2008), in indirect measures of cognitive capacity (e.g., using structural or functional brain imaging techniques; Bialystok et al., 2005; Garbin et al., 2010), and in cognitive reserve (i.e., protection against dementia onset; for recent reviews, see Bialystok, Craik, Green, & Gollan, 2009; Bialystok et al., 2012). These effects imply that bilingual language use entails a massive and constant exercise in cognitive control, which in turn strengthens non-linguistic control mechanisms for bilinguals relative to monolinguals. However, the precise mechanism that underlies these effects remains largely unexplored, although it is clear that identifying the specific aspects of bilingual language use that lead to cognitive advantages will result in a better understanding of both bilingualism and executive control.

Confusing in this area of research is the fact that the terms ''executive function'' and ''cognitive control'' are used to cover a range of abilities that although correlated are not unitary (Miyake & Friedman, 2011). Even the most parsimonious models of executive function usually refer to at least three components—working memory, inhibition or inhibitory control, and shifting or cognitive flexibility. Bilingual advantages have been investigated most intensively in the domain of inhibitory control, under the assumption that the constant competition arising between the language systems of bilinguals (Green, 1998; Kroll, Bobb, Misra, & Guo, 2008) leads to improved inhibitory abilities that might generalise outside the language domain (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Prior, 2012). However, there is ongoing debate about the role of inhibitory control in bilingual language production, and about the locus of bilingual advantages in inhibitory control, as well as the consistency of these results (Hilchey & Klein, 2011; Paap & Greenberg, 2013).

Fewer studies have focused on the domain of set-shifting, or cognitive flexibility, as a possible locus of bilingual advantages, although it arguably constitutes a more obvious place to look for an influence of bilingualism on executive control. Some theoretical accounts of bilingual language processing reject the proposal that bilinguals rely on inhibitory control to manage language competition (e.g., Costa, Miozzo, & Caramazza, 1999), but bilinguals clearly need to switch languages regularly in their daily lives, and many bilinguals switch back and forth between languages quite frequently in some settings. As such, one might expect to find more efficient switching in general in bilinguals, but research to date has yielded mixed results. Confirming the prediction that bilinguals should switch more efficiently, Prior and MacWhinney (2010) reported smaller switching costs for bilinguals relative to monolinguals in a non-linguistic switching paradigm. Within such paradigms performance for relatively easy single-task blocks is compared with performance on more difficult mixed-task blocks, in which participants alternate between two different tasks based on a cue. S*witching costs* contrast repeat trials (in which the task remains the same as on the previous trial) with switching trials (in which the task changes relative to the previous trial), and capture the local and immediate difficulty of task reconfiguration (Rubin & Meiran, 2005). In contrast, *mixing costs* contrasts trials in which no switching is involved, comparing responses in the single-task block to repeat trials in the mixed block, and capture the added difficulty of monitoring the more complex setting of the mixed block (Koch, Prinz, & Allport, 2005; Los, 1996, 1999). Of interest, although Prior and MacWhinney (2010) reported smaller switching costs for bilinguals, there were no differences between bilinguals and monolinguals in mixing costs—their responses were indistinguishable on single-trial blocks, and on non-shift trials in the mixed-task block.

A subsequent study seemed to confirm the sensitivity of *switching* rather than mixing to bilingual language use, and established an explicit connection between linguistic and non-linguistic switching, but also demonstrated some significant limitations on the extent to which bilinguals are advantaged in non-linguistic switching. Prior and Gollan (2011) found smaller non-linguistic switching costs in bilinguals relative to monolinguals, but only for Spanish-English bilinguals who reported switching languages often in daily language use, and only after controlling statistically for differences between bilinguals and monolinguals in socio-economic status. Mandarin-English bilinguals also participated in the study and were not advantaged relative to monolinguals. A possible explanation for the absence of a switching advantage in Mandarin-English bilinguals was that they reported switching languages significantly less often than the Spanish-English bilinguals. Further supporting the link between language switching and bilingual advantages, Spanish-English bilinguals switched *languages* more efficiently than Mandarin-English bilinguals in the language-switching task. These results suggest that bilingual advantages may be quite limited in scope (i.e., it was not replicated for all bilingual groups, and required controlling for factors unrelated to bilingualism that can also affect executive control), but do support a link between language control and non-linguistic control—specifically in the domain of switching, rather than mixing.

Within the task-switching literature, switching costs and mixing costs have been linked to different cognitive processes. Mixing costs are said to reflect more global processes of conflict monitoring and the demand of keeping two task-sets partially activated in the mixed blocks as opposed to in the single-task blocks. Switching costs, on the other hand, are thought to reflect the local, time-sensitive demands of actually managing activation levels to allow inhibition of the previous task-set and activation of the currently relevant task and response set (Prior & MacWhinney, 2010). Bilingual language use poses demands of both kinds—long-term maintenance of activation in two language systems, as well as flexible and timely shifting from one to the other, based on communicative intent and the specific interlocutor. Thus, although the findings described above found differences between bilinguals and monolingual mainly in switching costs, a theoretical argument could also be made for expected differences in mixing costs. Indeed, mixing costs are arguably more closely aligned with the monitoring processes identified by some to be a locus of bilingual advantages (e.g., Costa et al., 2009).

Several additional recent studies have attempted to clarify the link between bilingual language use and executive control benefits by directly comparing performance across tasks with a specific focus on switching. On the one hand these revealed significant and sometimes rather robust correlations. For example, Weissberger, Wierenga, Bondi, and Gollan (2012) reported that aging bilinguals who had difficulty with a non-linguistic switching task also made significantly more errors in a language-switching task than matched controls who had no trouble with the non-linguistic switching task. Similarly, Gollan, Sandoval, and Salmon (2011) found that aging bilinguals are more likely to switch languages unintentionally, and produce *language intrusion errors* if they also made many errors on a non-linguistic flanker task. Such relationships have also been reported in young bilinguals. Soveri, Rodriguez-Fornells, and Laine (2011) tested young adults and found that bilinguals who reported frequent language switching committed fewer errors in a non-linguistic task-switching paradigm. Festman, Rodriguez-Fornells, and Munte (2010) further reported that young adult bilinguals who were better able to maintain language control and avoid intrusions from the non-target language in a picture-naming task outperformed bilinguals more susceptible to language interference on several executive function measures, including tests of inhibition and cognitive flexibility. Finally, Linck, Schwieter, and Sunderman (2012) recently reported that young adult language learners who showed better inhibitory control in a non-linguistic task also incurred smaller switching costs in language switches involving their first language (L1).

On the other hand, there appear to be some serious limitations on the relationships between language control and performance in analogous non-linguistic control tasks—often within the same studies that report these relationships. Weissberger et al. (2012) found many more differences than similarities in the pattern of aging deficits seen across linguistic and non-linguistic versions of the switching paradigm. Specifically, when examining overall response speed, language control appeared to be better preserved into older age; namely, age-related slowing was much smaller in the language task than in the colour/shape task. Looking at switching and mixing costs, relative to young bilinguals, aging bilinguals exhibited larger switching and mixing costs in the language task (in RTs), but in the non-linguistic task only mixing-cost errors were affected by aging. Similarly, Gollan et al. (2011) concluded that the role of non-linguistic control for maintaining target language production must be quite limited because language control failure rates remained very low even in older bilinguals with substantial deficits in the non-linguistic task. Another recent study of younger bilinguals by Calabria, Hernández, Branzi, and Costa (2012) failed to find any significant correlations between linguistic and non-linguistic switching costs, and also reported a dissociation in the patterns of switching costs between the two tasks, namely symmetric switching costs for the two languages, but asymmetric switching costs in the non-linguistic task (see also Calabria, Branzi, Marne, Hernández, & Costa, 2013). However, differences between tasks could arise for a variety of reasons related to the specific implementation of language and task switching. Moreover, it is difficult to interpret null correlations particularly between difference scores (such as switching costs) which are notoriously noisy (Kopp, 2011; Miyake, Emerson, & Friedman, 2000).

In the current study, we further probed the relation between language control and non-linguistic cognitive control in a paradigm that allows for several converging ways of investigating these relations. Of interest, we tested the possibility of transfer between bilingual language control and non-linguistic task control more directly. Previous interpretations of bilingual advantages in executive control rely on two assumptions. First, that non-linguistic executive control ability can be improved with training, and second, that such training can transfer from language use to non-linguistic control. To test these assumptions we looked for evidence of transfer between tasks, in three groups of bilinguals, and also in one group of monolinguals, who first practised either linguistic or non-linguistic switching tasks, and then were tested a week later on the non-practised task. We asked if the two tasks would exhibit practice benefits, whether such benefits would remain a week after initial practice (both within-subject comparisons), and whether the non-practised task—either linguistic or non-linguistic switching—would exhibit any transfer of practice effects from the other task (a between-subjects comparison). This allowed us to test the critical question of whether training in one type of task—either linguistic or non-linguistic—would transfer to and improve performance in the other previously non-practised domain. Based on previously reported bilingual advantages in task switching, we anticipated that training with language switching might reduce colour/shape switching costs, perhaps particularly so for monolinguals who had no prior experience with language switching. Because of the putative common mechanism for linguistic and non-linguistic control hypothesised to underlie the reported bilingual advantages, it also seemed possible that we would observe transfer effects in both directions. That is, practice with linguistic control could facilitate performance on subsequent testing of non-linguistic control ability, but also practice with non-linguistic switching might improve language-switching control.

Our inclusion of different bilingual groups as well as monolinguals in the study, allowed us to further probe the importance of pre-experimental experience in language control for the patterns of similarity and difference across linguistic and non-linguistic control. Specifically, because monolinguals have no experience with language switching they might be more likely to exhibit transfer across domains. Finally, based on previously reported training studies we anticipated that non-linguistic control should improve with practice for all participants (e.g., Karbach & Kray, 2009). Regarding the effects of practice for language control, we predicted stronger training effects for monolinguals, especially for their rarely-used non-dominant language (see participant section for details). On the other hand, given the tremendous frequency with which bilinguals switch and mix languages, performance might be close to ceiling for this population, and might not improve much with further practice.

METHOD

Participants

The participants of the study were 61 early Spanish-English bilinguals, 29 early Mandarin-English bilinguals, and 54 English-speaking monolinguals were undergraduates at the University of California, San Diego, and participated in the study for course credit or payment. Bilinguals spoke Spanish or Chinese at home, and learned English at school on average at about age 4 (before age 8 at the latest). Of these, 12 Mandarin-English and 5 Spanish-English bilinguals who were not English-dominant at the time of testing (based on performance on a picture-naming test, further elaborated in the methods section) were excluded from analysis so as to achieve greater homogeneity in participant groups with respect to immersion in the dominant language. In addition, 31 late Hebrew-English bilinguals at the University of Haifa in Israel participated for course credit or payment. The Hebrew-English bilinguals were all Hebrew-dominant native speakers of Hebrew, and had studied English as a foreign language in a school setting from the age of 9 to 10. These participants conducted their daily life almost exclusively in

Hebrew. In attempting to match these late bilinguals to the early bilinguals tested in San Diego for proficiency level, we recruited students who had received high scores in the English portion of the Israeli equivalent of the SAT (a score of at least 135 out of a maximal score of 150), which conferred on them exemption from enrolling in further English courses at the university level. Nonetheless, the Israeli students were still less balanced in their command of the two languages than the participants tested in the US based on self-reporting. Finally, the Israelis were older on average than the Americans, because they had completed mandatory military service before enrolling at university (see also Prior, 2012).

Materials and procedure

Participants completed two experimental tasks and two background measures. Computerised tasks for the participants in San Diego were presented using PsyScope 1.2.5 (Cohen, MacWhinney, Flatt, & Provost, 1993) on a Macintosh computer with a 17-inch colour monitor. Naming times were recorded using microphones connected to PsyScope response boxes. Computerised tasks for the participants in Haifa were presented using E-prime 2.0 on a PC computer with a 19-inch colour monitor. Naming times were recorded using microphones connected to a serial response box (Psychological Software Tools Inc., Pittsburgh, PA). In both locations spoken responses were recorded live using digital recorders, and coded for accuracy off-line. Participants were seated approximately 60 cm from the monitor.

Background measures

Language history questionnaire. Participants in San Diego completed the questionnaire in English, and bilinguals in Haifa completed a Hebrew translation. The questionnaire included questions regarding their history and context of acquiring the languages they know, present language use, language proficiency and demographic variables. Self-ratings were recorded using Likert scales. These data are presented in Table 1. Such questionnaires are widely used in bilingual research, and are significantly correlated with objective measures of language proficiency (Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012; Marian, Blumenfeld, & Kaushanskaya, 2007). Participants completed the questionnaire independently in approximately 10 min on the first day of testing.

As can be seen in Table 1, the monolingual participants reported having some limited proficiency in another language, mostly one learned as a foreign language in a formal educational setting. This was important in the present study, because monolinguals were required to name digits in a language other than English, when performing the language-switching task (see below). For ease of exposition, we refer to this language as the "non-dominant" language for monolinguals, even though strictly speaking it is critical to keep in

TABLE 1
Participant characteristics

	Monolinguals (*n* = 54)	*Hebrew-English* (*n* = 31)	*Mandarin-English* (*n* = 17)	*Spanish-English* (*n* = 56)
Age	20.1	25.0	20.0	20.3
English self-rated proficiency	6.9	5.8	6.7	6.5
Other language self-rated proficiency	2.9	7	4.50	5.9
English MINT	31.2	24.4	31	29.4
Other language MINT	N/A	31.6	23.2	23.2
Primary caregiver yrs education	15.1	15.6	15.5	10.7
Secondary caregiver yrs education	15.2	14.5	14.9	10.2
Participant yrs education	13.5	13.4	13.6	13.9
English percentage daily use	98.5	12.4	93.1	80.8
Age of first exposure to English (yrs)	0.8	8.2	2.2	4.1
How often switch languages	N/A	1.6	2.9	3.4

Language proficiency was rated on a 1 to 7 scale. Ratings presented here are averages across speaking, listening, reading and writing. Language-switching frequency was rated on a 1 to 5 scale. Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

mind that the monolinguals are in fact functionally monolingual, with extremely limited ability to function in any language other than English, and had not learned any language other than English in early childhood.

Multilingual Naming Test (MINT). Participants were asked to name 33 black and white line drawings in each language. Items were even items (plus one) taken from MINT (Gollan et al., 2012)—a picture-naming test developed for use with English, Spanish, Mandarin, and Hebrew, with items in order of estimated increasing difficulty. All Hebrew-English bilinguals named more pictures correctly in Hebrew than in English, 54 Spanish-English bilinguals named more pictures correctly in English, and 2 had identical naming scores in the two languages (and were classified as English-dominant and remained in the analyses); 17 Mandarin-English bilinguals named more pictures correctly in English and were included in the analyses. Bilingual participants were tested in both languages on the second day of testing with language order counterbalanced across participants. Monolinguals completed MINT on the second day of testing in English only. Means are presented in Table 1.

Analysis of the participant characteristics showed that the Hebrew-English bilinguals were older than the other participant groups ($p < .01$) who did not differ from each other (all $p > .6$), but there were no differences in level of education ($p = .39$). In ratings of the dominant language, the Hebrew-English bilinguals and the monolinguals rated themselves as having higher proficiency than the Spanish-English and Mandarin-English bilinguals ($ps < .05$), but there were no other significant differences. In the non-dominant language, the monolinguals rated themselves significantly lower than all other participants ($ps < .01$), and the Mandarin-English bilinguals also rated themselves lower than the Hebrew-English and Spanish-English bilinguals ($ps < .01$), who did not differ from each other ($p = .39$). In the objective assessment of language proficiency, the Spanish-English bilinguals had lower scores on MINT in their dominant language than the other three groups (all $ps < .01$), which did not differ from each other (all $ps > .19$). Conversely, there were no significant differences in non-dominant language MINT scores across the three bilingual groups ($p = .30$).

Possibly explaining their lower dominant-language naming scores, Spanish-English bilinguals had primary and secondary caregivers with significantly fewer years of education than those of all other participant groups (both $ps < .01$), which did not differ from each other (all $ps > .39$). Monolinguals reported using their dominant language (English) a higher percentage of the time than bilinguals ($p < .01$), and the Spanish-English bilinguals reported using their dominant language a lower percentage of the time than the Mandarin-English and Hebrew-English bilinguals (both $ps <$ .05), who did not differ from each other ($p = .17$). The groups all differed significantly from each other in their age of first exposure to English ($F(3, 154) = 93.94$, $MSE = 572.48$, $p < .01$). The Hebrew-English bilinguals reported switching languages less often than the two other bilingual groups ($ps < .01$), who did not differ significantly from each other in this sample ($p = .31$).

Experimental tasks

Colour/shape-switching sequence. Participants judged red and green circles and triangles for colour or shape with a spoken response (e.g., saying "red" or "green" when prompted with a colour cue, and "circle" or "triangle" when prompted with a shape cue). Participants tested in San Diego responded in English, their dominant language, and participants tested in Israel responded in Hebrew, their dominant language, (i.e., with the words "adom" or "yarok" when prompted with a colour cue, and "igul" or "meshulash" when prompted with a shape cue). Each trial started with a fixation cross presented for 350 ms, followed by a blank screen for 150 ms. The task cue then appeared on the screen for 250 ms, 3.5 cm above the fixation cross. The cue for the colour task was a colour gradient, and the cue for the shape task was a row of small black shapes (5 by 1.2 cm). The cue remained on the screen, and the target appeared in the centre of the screen. Targets were red or green circles (3 cm radius) and triangles (3 cm base, 2.5 cm height). The cue and target remained on the screen until the participant responded, or for a maximum duration of 3 seconds. An 850 ms inter-trial blank screen interval was presented before the onset of the following trial. Participants completed three parts of the experiment, comprising a sandwich design. First, two single-task blocks (colour and shape, order counterbalanced across participants), each including 12 practice trials and 20 experimental trials. Second, 16 mixed-task practice trials, followed by 4 mixed-task blocks of 20 trials each. In each mixed block, half the trials were switching trials (where the task was different from that performed on the previous trial) and half were repeat trials (retaining the same task from the previous trial), of both the colour and shape tasks, randomly ordered with a maximum of 4 consecutive trials of the same type. Each stimulus appeared 5 times in each block. Two additional dummy trials were added at the beginning of each block and were not included in the analysis. Finally, in the third part of the experiment, participants again performed two single-task blocks, presented in the opposite order from that used in the first part. Participants were notified regarding the nature of each block performed (single or mixed). The sandwich design enables a comparison of 40 switching trials, 40 non-switching trials, and 80 single-task trials (40 colour and 40 shape). In this design participants gain practice with each task before completing the mixed-task blocks, and the estimation of single-task proficiency includes both initial and later (well-practised) responses, thus avoiding exclusive influence of order effects on mixed-block performance.

Language-switching sequence. The set-up of the language-switching task was parallel to that of the colour/shape-switching task, and preserved the same trial sequence and timing parameters. The stimuli in all blocks were single digits (1 to 9), and participants named the digit out loud as quickly as possible. The cues were the American flag for English, the Mexican flag for Spanish, the Chinese flag for Mandarin and the Israeli flag for Hebrew. Monolinguals were presented the United Nations flag and instructed to use whichever second language in which they could most easily name the numbers 1 to 9. Languages of choice included Spanish, French, German, Japanese, Arabic, Mandarin, Cantonese, Farsi, Korean, Tagalog, Hindi, Vasaya, and Vietnamese. Monolinguals were instructed to use only a single language other than English to name digits when cued by the UN flag, and not to intermix digit names from several languages, even if these were known to them. Participants first performed two single-language naming blocks, one in English and the other in their other language, with order counterbalanced across participants. Each block included 12 practice trials and 20 experimental trials. Next they completed 16 mixed-language practice trials, followed by 4 mixed-language blocks, each including 20 experimental trials, half in each language. Additionally, half the trials were repeat trials (cued with the same language as the previous trial) and half were switching trials (where the response language changed from the previous trial). The same digit never appeared on two consecutive trials, and there were no sequences of serially ordered numbers longer than 2, either ascending or descending. Finally, there were at most 4 consecutive trials of the same type (switching or repeat). The mixed-language blocks were followed by two additional single-language blocks of 20 trials each, in the opposite order than that used in the first part of the experiment. Every digit appeared either 2 or 3 times in each block, and across the entire task, every participant saw each digit either 18 or 19 times (including the dummy trials).

An important feature of the present design was the close match across the non-linguistic and language-switching tasks. In all cases participants spoke their responses, and these responses were univalent, namely, each task required using a unique set of responses (the words “green” and “red” for the colour task, digit numbers in English for the English naming-task, and so on). The visual cues were compatible across the two tasks, and all timing parameters were kept constant. The main difference between the two tasks was in the number of different stimuli. For the non-linguistic switching there were 4 stimuli associated with 4 different responses, and in the language-switching task there were 9 stimuli associated with 18 possible responses. However, across both paradigms the cue-stimuli pairings were identical across the two tasks, namely, each stimulus was equally likely to appear with each of the task or language cues, which would decrease the probability that participants might form implicit notions of cue and stimuli transitions. Further, in both paradigms the cue always preceded the stimulus, arguably allowing participants to at least partially reinstate the task-set before seeing any particular stimulus (Koch et al., 2005; Koch & Allport, 2006). The main remaining difference between the two paradigms was that in the non-linguistic switching task immediate response repetitions occurred occasionally, whereas no immediate stimulus repetitions appeared in the language-switching task.

Training and transfer

Each participant was tested on two days, exactly one week apart (e.g., participants tested on a Monday on Day 1 were retested on the following

Monday for Day 2, with just 3 exceptions who were scheduled 8 instead of 7 days later, and 2 who were tested 6 instead of 7 days later). One switching sequence (either language or colour/shape) was assigned to be the training task, and the other was assigned to be the transfer task, counterbalanced across participants in each language group. On the first day of testing, participants performed one full sequence (2 single blocks, 4 mixed blocks, 2 single blocks) of the training task (Training1), and then immediately completed a second full sequence of the same task (Training2). On the second day of testing, participants first performed one full sequence of the transfer task (Transfer) and then a final full sequence of the training task from the previous week (Training3; see Table 2 for an illustration).

RESULTS

Data analyses included language group as a factor to determine if bilinguals differed from monolinguals, and further if the different bilingual groups (who varied in language combinations and acquisition histories) exhibited different training and transfer effects.

Within-task training effects

Before looking for transfer of practice effects across tasks it was necessary to establish that practice significantly improved performance within each of the two tasks. To this end, we examined immediate improvement from the Training1 sequence to the Training2 sequence on the first day of testing, and also whether these gains were maintained one week later by comparing performance of the Training3 sequence on the second day of testing with performance of the Training1 sequence one week earlier. In this context, we analysed mean RTs of performance collapsing across all trial types (single, repeat, switching), as well as switching costs (which subtract repeat RTs from switching RTs in the mixed block) and mixing costs (which subtract single-block RTs from repeat RTs in the mixed block) as indicators of improvement in meeting the demands of cognitive control.

To examine within-task practice effects, we conducted two-way ANOVAs on mean RTs from the three training sequences (see Tables 3 and 4 and Figure 1). In the language-switching task we examined the dominant and non-dominant language separately because we anticipated—and were particularly interested in—significant differences between bilinguals and monolinguals in the non-dominant language. For consistency of presentation across tasks we analysed colour and shape responses separately, though in this case we did not have a-priori expectations of differences across groups. As noted above, self-rated language dominance was confirmed based on performance on MINT—bilinguals named more pictures correctly in their dominant language, which was Hebrew for the Hebrew-English bilinguals and English for all other participants. We compared the Training2 and Training1 sequences to see the effect of

TABLE 2
Study design

Sandwich design of switching paradigms		
	Task switching	*Language switching*
Blocks 1–2	Single-task blocks (1 colour & 1 shape, order counterbalanced)	Single-language blocks (1 English & 1 other, order counterbalanced)
Blocks 3–6	4 mixed colour/shape blocks	4 mixed English/other blocks
Blocks 7–8	Single-task blocks (1 colour & 1 shape, order reversed from blocks 1 & 2)	Single-language blocks (1 English & 1 other, order reversed from blocks 1 & 2)

Counterbalancing of training and transfer sequences			
Time point	*Training condition*	*Subject group A*	*Subject group B*
Day 1	Training1	Task switching	Language switching
	Training2	Task switching	Language switching
Day 2	Transfer	Language switching	Task switching
(one week later)	Training3	Task switching	Language switching

TABLE 3
Language-switching performance

Language-switching performance on Day 1 and Day 2, mean reaction times and costs in millisecond (SEM), by dominance

		Dominant language			*Non-dominant language*		
		Training1	*Training2*	*Training3*	*Training1*	*Training2*	*Training3*
Monolinguals	Single	466	456	477	614	585	594
(*n*=27)		(8.7)	(8.2)	(12.7)	(21.9)	(18.3)	(15.4)
	Repeat	530	502	535	660	621	623
		(13.4)	(12.2)	(17.5)	(28.1)	(18.7)	(17.1)
	Switch	577	573	592	670	633	633
		(17.0)	(17.9)	(21.6)	(25.8)	(17.7)	(18.4)
	Mixing	64	45	58	46	35	29
	cost	(9.6)	(8.3)	(7.6)	(11.2)	(7.3)	(10.8)
	Switching	47	71	57	10	12	10
	cost	(8.6)	(9.8)	(9.7)	(15.5)	(9.9)	(10.5)
Hebrew-English	Single	440	433	448	503	506	515
(*n*=15)		(14.2)	(11.4)	(16.1)	(17.5)	(17.8)	(20.6)
	Repeat	485	473	489	525	520	522
		(15.6)	(15.0)	(20.2)	(14.2)	(17.7)	(17.2)
	Switch	503	490	490	544	547	550
		(17.2)	(20.9)	(23.9)	(17.9)	(23.3)	(31.6)
	Mixing	45	40	41	22	14	8
	cost	(9.3)	(7.5)	(14.3)	(4.9)	(10.1)	(12.3)
	Switching	18	17	2	19	27	27
	cost	(8.9)	(12.1)	(9.5)	(10.6)	(11.5)	(21.3)
Mandarin-English	Single	489	485	486	481	479	477
(*n*=11)		(10.9)	(15.8)	(12.8)	(11.6)	(14.1)	(9.0)
	Repeat	577	556	547	563	548	524
		(29.8)	(23.6)	(38.4)	(18.7)	(17.9)	(22.3)
	Switch	612	612	588	629	596	575
		(27.0)	(32.9)	(40.3)	(28.5)	(23.2)	(28.0)
	Mixing	88	71	61	82	68	47
	cost	(27.5)	(20.4)	(33.4)	(16.1)	(19.7)	(21.8)
	Switching	35	56	41	66	49	51
	cost	(7.4)	(18.9)	(11.4)	(14.0)	(10.5)	(14.3)
Spanish English	Single	537	527	532	525	517	517
(*n*=26)		(6.5)	(14.0)	(13.9)	(13.0)	(12.2)	(10.1)
	Repeat	606	606	597	596	592	588
		(22.6)	(22.4)	(19.7)	(21.4)	(18.1)	(19.8)
	Switch	635	635	610	609	606	594
		(25.5)	(25.4)	(18.9)	(20.9)	(21.2)	(19.1)
	Mixing	69	79	65	71	75	72
	cost	(13.5)	(13.5)	(12.0)	(12.9)	(9.1)	(13.8)
	Switching	29	29	13	13	15	5
	cost	(6.4)	(8.3)	(6.3)	(8.9)	(8.7)	(6.3)

Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

immediate practice, and also compared the Training3 and Training1 sequences to examine whether the gains were maintained one week later. Training sequence was a within-participant variable. To consider participant group effects, we conducted one set of analyses comparing monolinguals to bilinguals as a between-participant factor, and a second set of analyses comparing the three bilingual groups (Spanish-English, Hebrew-English and Mandarin-English), again with group as a between-participant factor.

Overall RT effects

To foreshadow our results, we found significant same-day training effects for both language switching and task switching, for all participants.

TABLE 4
Language-switching performance

Task-switching performance on Day 1 and Day 2, mean reaction times and costs in millisecond (SEM), by task

		Colour			*Shape*		
		Training1	*Training2*	*Training3*	*Training1*	*Training2*	*Training3*
Monolinguals	Single	511	497	503	471	449	470
($n = 27$)		(14.2)	(12.3)	(10.1)	(13.4)	(12.6)	(11.1)
	Repeat	593	563	556	561	524	542
		(15.7)	(17.2)	(15.0)	(15.4)	(11.4)	(16.4)
	Switch	609	581	588	606	570	580
		(18.2)	(17.4)	(16.7)	(18.0)	(18.9)	(15.5)
	Mixing	82	66	54	89	75	71
	cost	(9.6)	(11.2)	(9.9)	(10.9)	(10.1)	(12.3)
	Switching	16	18	31	45	46	38
	cost	(9.5)	(9.4)	(7.3)	(10.8)	(11.3)	(11.2)
Hebrew-English	Single	463	459	463	531	503	498
($n = 16$)		(18.2)	(17.1)	(17.5)	(21.1)	(17.9)	(18.7)
	Repeat	529	494	487	603	545	559
		(24.6)	(26.1)	(18.7)	(21.3)	(19.7)	(23.1)
	Switch	559	526	526	658	608	609
		(22.7)	(25.9)	(23.9)	(27.1)	(30.3)	(25.3)
	Mixing	66	35	24	72	42	61
	cost	(13.9)	(20.2)	(8.2)	(18.0)	(12.9)	(11.2)
	Switching	30	32	39	55	63	50
	cost	(10.3)	(16.7)	(13.6)	(23.2)	(17.2)	(13.9)
Mandarin-English	Single	542	515	520	522	484	508
($n = 6$)		(24.5)	(28.5)	(27.8)	(30.8)	(37.8)	(32.9)
	Repeat	592	551	542	594	573	586
		(20.6)	(24.4)	(36.3)	(30.1)	(39.9)	(36.9)
	Switch	613	595	591	653	600	625
		(29.5)	(28.7)	(38.6)	(42.7)	(47.6)	(49.8)
	Mixing	50	36	22	72	89	78
	cost	(18.0)	(13.4)	(16.3)	(9.9)	(18.8)	(17.1)
	Switching	21	44	49	59	27	40
	cost	(18.1)	(16.9)	(7.0)	(23.4)	(15.1)	(31.4)
Spanish-English	Single	570	566	559	563	544	543
($n = 30$)		(12.3)	(15.3)	(10.0)	(15.5)	(14.9)	(14.1)
	Repeat	674	632	629	648	624	611
		(17.2)	(16.1)	(13.9)	(16.4)	(17.2)	(15.7)
	Switch	678	647	662	700	670	672
		(21.8)	(18.2)	(17.9)	(20.2)	(19.0)	(21.5)
	Mixing	103	66	70	85	80	68
	cost	(12.3)	(9.6)	(10.5)	(12.5)	(8.9)	(10.4)
	Switching	4	15	33	52	46	61
	cost	(12.1)	(10.7)	(10.6)	(11.6)	(9.8)	(13.0)

These training effects were largely maintained one week later, though more consistently for the colour/shape task than for the language-switching task. It is worth noting that we also found participant group differences in a number of comparisons, but these did not factor heavily in our interpretation of training and transfer effects, which rest primarily on results found when collapsing all participant groups together, including bilinguals and monolinguals.

Dominant language. In the analysis of training effects for the dominant language, there was significant improvement from the Training1 sequence to the Training2 sequence ($F(1, 77) = 6.54$, $MSE = 556.85$, $p < .05$, $\eta_p^2 = .08$), but these gains were not maintained one week later in the Training3 sequence ($F < 1$). This pattern was consistent across bilinguals and monolinguals (both $ps > .10$). When comparing the three bilingual groups, the only significant finding was a

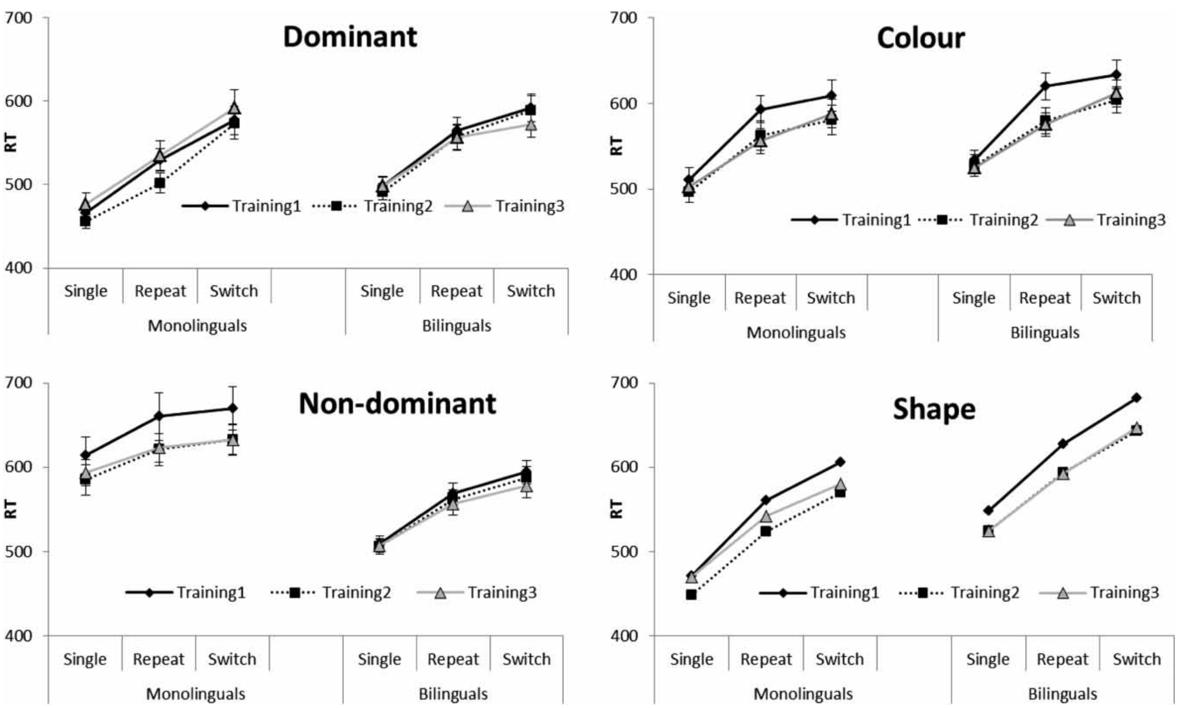

Figure 1. Training effects in RT for all four tasks. Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

main effect of group, because the Hebrew-English bilinguals were significantly faster than the Spanish-English and Mandarin-English bilinguals (both *p*s $<.05$), who did not differ from each other ($p > .22$). Because the Hebrew-English bilinguals were late bilinguals, a possible interpretation of this result is related to bilingual disadvantages for language tasks. Consistent with this hypothesis, monolinguals also responded significantly more quickly in their dominant language than the Spanish-English early bilinguals ($p < .01$) but not the Mandarin-English bilinguals ($p = .25$; numbers trended 27 ms in the right direction but this last comparison is underpowered due to the small number of Mandarin-English bilinguals).

Non-dominant language. For the non-dominant language, there was again significant improvement from the Training1 sequence to the Training2 sequence ($F(1, 77) = 14.35$, $MSE = 1046.20$, $p < .01$, $\eta_p^2 = .16$), but this was qualified by a two-way interaction ($F(1, 77) = 7.46$, $MSE = 1046.20$, $p < .01$, $\eta_p^2 = .09$), because the monolinguals significantly improved (a reduction of 35 ms, $p < .01$) but the bilinguals did not (a reduction of 6 ms, $p = .28$). In addition, there was a main effect of language group, because bilinguals responded more quickly than monolinguals ($F(1, 77) = 13.85$, $MSE = 14924.74$, $p < .01$, $\eta_p^2 = .15$). A similar pattern was evident when comparing the Training3 sequence to the Training1 sequence—there was a significant main effect of sequence ($F(1, 76) = 6.86$, $MSE = 2107.42$, $p < .05$, $\eta_p^2 = .08$), but although the numeric improvement was much larger for monolinguals (32 ms) than for bilinguals (8 ms), the two-way interaction with language group was not significant ($p = .13$). Again, bilinguals responded more quickly than monolinguals, ($F(1, 76) = 17.50$, $MSE = 13252.75$, $p < .01$, $\eta_p^2 = .19$). There were no significant differences between the three bilingual groups ($p > .10$).

Colour task. In the colour task, there was significant improvement from the Training1 sequence to the Training2 sequence ($F(1, 77) = 35.12$, $MSE = 614.10$, $p < .01$, $\eta_p^2 = .31$), which was maintained for the Training3 sequence, which was significantly better than the Training1 sequence ($F(1, 77) = 9.95$, $MSE = 1982.42$, $p < .01$, $\eta_p^2 = .11$).This pattern was stable across bilinguals and monolinguals ($F < 1$). In comparing the three bilingual groups, there was a significant main effect of group ($F(2, 49) = 12.23$, $MSE =$

12986.69, $p < .01$, $\eta_p^2 = .33$), and *post hoc* comparisons demonstrated that the Hebrew-English bilinguals were significantly faster than the Spanish-English bilinguals ($p < .01$), but no other group differences were significant. Similarly, as for dominant-language responses, monolinguals also responded more quickly than Spanish-English bilinguals ($p < .01$), but not Mandarin-English bilinguals ($p = .76$).

Shape task. In the shape task, there was again significant improvement from the Training1 sequence to the Training2 sequence ($F(1, 77) = 46.82$, $MSE = 775.89$, $p < .01$, $\eta_p^2 = .38$), which was maintained for the Training3 sequence ($F(1, 77) = 8.50$, $MSE = 2235.47$, $p < .01$, $\eta_p^2 = .09$). In both comparisons there was also a main effect of group, because bilinguals were faster than monolinguals on the shape task (both *ps* $< .01$). There were no significant differences when comparing the three bilingual groups.

Summarising the simple training effects, all tasks exhibited some Day 1 training effects (faster responses in Training2 than in Training1), though for the non-dominant language it was primarily monolinguals exhibiting this effect. Similarly, only monolinguals exhibited non-dominant-language training effects that were still present one week later, whereas all participants exhibited such training effects for the colour and shape tasks. In addition, bilinguals responded more quickly than monolinguals in the non-dominant language and in the shape task, but there were some tendencies towards disadvantages for early Spanish-English bilinguals in the dominant language (Mandarin-English bilinguals exhibited a non-significant trend in this direction) and in the colour task. The late Hebrew-English bilinguals did not show these disadvantages.

Switching and mixing costs

We then calculated the mixing costs (repeat trials in the mixed-task blocks minus trials in the single-task blocks) and the switching costs (switching trials minus repeat trials in the mixed-task blocks) for each participant for each task for each training sequence. Foreshadowing the results, training tended to reduce mixing costs, but not switching costs.

Dominant-language switching costs. In the dominant language, switching costs increased from the Training1 sequence to the Training2 sequence, there was a main effect of training sequence ($F(1, 77) = 4.78$, $MSE = 1511.39$, $p < .05$, $\eta_p^2 = .06$). This increase was larger for monolinguals (difference of 24 ms), who improved in non-switching trials much more than in switching trials, but not for bilinguals (difference of 4 ms), but the two-way interaction between sequence and language group was not significant ($F(1, 77) = 2.43$, $MSE = 1511.39$, $p = .12$, $\eta_p^2 = .03$). There was also a main effect of group, because monolinguals had overall larger switching costs than bilinguals ($F(1, 77) = 13.78$, $MSE = 2322.17$, $p < .01$, $\eta_p^2 = .15$). When comparing the Training3 sequence to the Training1 sequence, this effect was no longer evident ($F < 1$), and the only significant effect was the main effect of group ($F(1, 76) = 17.50$, $MSE = 1865.83$, $p < .01$, $\eta_p^2 = .19$) due to the larger switching costs of the monolinguals. Comparing the three bilingual groups, there was no significant effect of group ($F(2, 49) = 2.78$, $MSE = 1745.51$, $p = .07$, $\eta_p^2 = .10$; the marginal trend reflected smaller dominant-language switching costs for Mandarin-English than Hebrew-English bilinguals).

Non-dominant-language switching costs. In the non-dominant language, there was no reduction in switching costs from the Training1 sequence to the Training2 sequence ($F < 1$) or to the Training3 sequence ($F < 1$), and no differences between the bilinguals and the monolinguals ($F < 1$). When comparing the three bilingual groups, there was a significant main effect of group ($F(2, 48) = 5.80$, $MSE = 3954.59$, $p < .01$, $\eta_p^2 = .20$), and *post hoc* comparisons showed that the Mandarin-English bilinguals had significantly larger switching costs for the non-dominant language than both other groups (*ps* $< .05$), which did not differ significantly from each other ($p = .25$; see also Prior & Gollan, 2011).

Dominant-language mixing costs. The analysis of mixing costs was conducted in the same manner to that described for switching costs. In the dominant language, there was no significant improvement from the Training1 sequence to the Training2 ($p = .08$) sequence or to the Training3 sequence ($p = .29$), and no difference between monolinguals and bilinguals ($F < 1$). There were also no significant differences when comparing the three bilingual groups ($p = .28$).

Non-dominant-language mixing costs. Similarly, in the non-dominant language there was no reduction in mixing costs from the Training1 sequence to the Training2 sequence, or to the Training3 sequence, and no difference between monolinguals and bilinguals. When comparing the three bilingual groups, the only significant effect was a main effect of group ($F(2, 48) = 6.68$, $MSE = 6818.75$, $p < .01$, $\eta_p^2 = .22$), and *post hoc* comparisons showed that the Hebrew-English bilinguals had significantly smaller mixing costs to the non-dominant language across all three training sequences than did the Mandarin-English and the Spanish-English bilinguals (both *ps* < .05), who did not differ from each other ($p = .69$). The finding of smaller mixing costs in the non-dominant language for late bilinguals is consistent with previous literature on language switching, in which proficient bilinguals show symmetrical costs for both languages, and less proficient bilinguals show larger costs in the dominant language and smaller costs in the non-dominant language (though note that monolinguals did not show smaller switching costs in the non-dominant language than Hebrew-English bilinguals).

Colour and shape tasks switching costs. In the colour task, there was no reduction in switching costs from the Training1 sequence to the Training2 sequence ($F < 1$) and switching costs on the Training3 sequence were reliably larger than on the Training1 sequence ($F(1, 77) = 5.58$, $MSE = 2373.48$, $p < .05$, $\eta_p^2 = .07$)—that is, there was an increase in switching costs on the second day of testing in comparison to the first, and therefore no evidence for a training effect that persisted over the one-week period. There were no differences between the bilinguals and the monolinguals ($F < 1$), or between the three bilingual groups ($p = .33$). Similarly, in the shape task, there was no reduction in switching costs from the Training1 sequence to the Training2 sequence or to the Training3 sequence (both $F < 1$), and no differences between bilinguals and monolinguals (both *ps* > .25), or between the three bilingual groups ($F < 1$).

Colour and shape tasks mixing costs. In the parallel analyses of mixing costs, there was a significant reduction in mixing costs for the colour task from the Training1 sequence to the Training2 sequence ($F(1, 77) = 9.76, MSE = 2185.87, p < .01$, $\eta_p^2 = .11$), which was maintained one week later in the Training3 sequence ($F(1, 77) = 13.24$, $MSE = 2715.76$, $p < .01$, $\eta_p^2 = .15$). There were no differences between bilinguals and monolinguals, but there was a significant main effect of group when comparing the three bilingual groups ($F(2, 49) = 7.11$, $MSE = 4306.75$, $p < .01$, $\eta_p^2 = .23$). *Post hoc* analyses showed that the Spanish-English bilinguals had significantly larger mixing costs on the colour task than did the Hebrew-English and the Mandarin-English bilinguals (both *ps* < .05), who did not differ from each other ($p = .77$). Finally, the analysis for mixing costs in the shape task revealed no immediate or delayed improvement in mixing costs, no differences between bilinguals and monolingual, and no differences between the three bilingual groups.

Summarising the within-task training effects, there was some immediate reduction in RTs for the dominant language, but it did not survive one week later. In the non-dominant language, practice significantly speeded responses for monolinguals but not bilinguals, and monolinguals maintained their improved performance a week later. There were no significant reductions in switching costs or mixing costs in either of the languages, for any of the participant groups. In contrast, training significantly speeded responses in the colour/shape task for all participant groups, both immediately and after a week's delay. Further, although there was no reduction in switching costs following training, there was a significant reduction in mixing costs in the colour task but not the shape task, both immediately and after a week, for all participant groups. These results set the stage for finding cross-task transfer effects in the direction expected for explaining bilingual advantages in non-linguistic switching—particularly for the colour/shape task, which appeared to allow for improvement with training. In contrast, transfer effects on the language task might be expected only for monolinguals in the non-dominant language, whereas little transfer should be expected for bilinguals, who appeared to be close to ceiling levels of performance in both languages.

A number of other significant group effects were found; for example, Spanish-English bilinguals responded more slowly in the dominant language and in the colour task, bilinguals responded more quickly in the non-dominant language and the shape task, monolinguals but not bilinguals exhibited increased switching costs with training on Day 1, and Hebrew-English bilinguals exhibited smaller mixing costs. Finally, monolinguals exhibited larger switching costs than bilinguals in the dominant language, but bilinguals were not advantaged in non-linguistic switching generally (as reported for Mandarin-English bilinguals in Prior & Gollan, 2011). We do not interpret these differences any further because they were not predicted a priori, and because there were no group differences in transfer effects (as reported below), which was of greater interest.

Cross-task transfer effects

To examine the possibility of cross-task transfer of practice, we compared the performance of participants who completed the language switching task as the Training1 sequence with the performance of participants who completed the language task as the Transfer sequence on the second day of testing. Similarly, we compared performance of the task switching when it was the Training1 sequence and when it was the Transfer sequence (see Table 5 and Figure 2). These between-subjects comparisons ask whether participants who practised each of the training tasks exhibited transfer effects and performed the new task on Day 2 more quickly than those who did not practise the task (but rather performed it in the Training1 sequence on the first day of testing). To foreshadow our results, in contrast to the stable within-task training effects, cross-task transfer effects were limited to reduced mixing costs in the non-dominant language following training with the colour/shape task.

Dominant language. When examining performance on the dominant language, there were no significant transfer facilitation effects ($F < 1$), and no differences between bilinguals and monolinguals ($p = .28$). Similarly, switching costs were not smaller for the dominant language after training with the colour/shape task ($F < 1$) and neither were mixing costs ($F < 1$), but bilinguals did have significantly smaller switching costs than monolinguals ($F(1, 154) = 6.35$, $MSE = 1816.64$, $p < .05$, $\eta_p^2 = .04$).

Non-dominant language. The non-dominant language did not show any transfer facilitation effects on overall response times ($F < 1$) but did show a main effect of group, because bilinguals were faster than monolinguals ($F(1, 154) = 45.29$, $MSE = 8150.80$, $p < .01$, $\eta_p^2 = .23$). There was no evidence of transfer in the switching costs ($F < 1$), but again there was a main effect of group, because monolinguals had significantly smaller switching costs than bilinguals ($F(1, 154) = 6.86$, $MSE = 3648.82$, $p < .05$, $\eta_p^2 = .04$).

The analysis of mixing costs, however, did demonstrate a significant effect of transfer ($F(1, 154) = 4.71$, $MSE = 2938.31$, $p < .05$, $\eta_p^2 = .01$). That is, relative to participants who had no practice with any task when they completed the language task, prior training with the colour/shape task led participants to have smaller mixing costs in the non-dominant language one week later when they completed the language-switching task for the first time. It might seem that this effect should have been driven exclusively by monolinguals, who would have had little (or no) prior experience with language switching; however, as can be seen in Table 5, all participant groups exhibited trends in this direction—and the transfer effect was not significant in any participant group on its own (Mandarin-English, $p = .06$; Spanish-English, $p = .08$; Hebrew-English, $p = .45$; monolinguals, $p = .39$)

Colour/shape tasks. For the colour task, there was no transfer facilitation in the overall RTs ($p = .20$) in the switching costs ($p = .07$) or in the mixing costs ($F < 1$), and there were no differences between bilinguals and monolinguals ($F < 1$). In the shape task, there was again no facilitation in overall RT following training with the language task ($p = .08$) but there was a main effect of language group ($F(1, 154) = 18.85$, $MSE = 8237.17$, $p < .01$, $\eta_p^2 = .1$), because monolinguals were significantly faster than bilinguals. Finally, there were no transfer effects in the switching costs ($F < 1$), and there was a marginally significant transfer effect in the wrong direction in the analysis of mixing costs ($F(1, 154) = 3.78$, $MSE = 5216.52$, $p = .054$, $\eta_p^2 = .02$). That is, participants who trained with the language task exhibited *larger* mixing costs for the shape task than those who performed it on the first day of training.

In summary, transfer effects were quite limited in scope. Only the non-dominant language exhibited a significant transfer benefit from training with the colour/shape task, in the form of a reduction in mixing costs. This transfer effect was not greater for monolinguals than for bilinguals (as might have been expected), and there was no significant transfer facilitation effect onto the colour/shape task (as would be needed to explain bilingual advantages). Instead, prior practice with the language task appeared to increase mixing costs in the colour/shape task.

TABLE 5
Mean RT (SEM) for training and transfer tasks

Mean RT (SEM) for dominant and non-dominant languages as training and as transfer task, by language group

		Dominant		*Non-dominant*	
		Training1	*Transfer*	*Training1*	*Transfer*
Monolinguals ($n = 54$)	Single	466 (8.7)	480 (9.2)	614 (21.9)	646 (26.9)
	Repeat	530 (13.4)	546 (11.0)	660 (28.1)	679 (24.4)
	Switch	577 (17.0)	597 (13.6)	670 (25.8)	678 (18.0)
	Mixing cost	64 (9.6)	67 (8.4)	46 (11.2)	32 (11.4)
	Switching cost	47 (8.6)	51 (9.1)	10 (15.5)	−1 (15.6)
Hebrew- English ($n = 31$)	Single	440 (14.2)	441 (14.3)	503 (17.5)	511 (13.40
	Repeat	485 (15.6)	474 (21.2)	525 (14.2)	524 (19.8)
	Switch	503 (17.2)	510 (20.9)	544 (17.9)	563 (27.3)
	Mixing cost	45 (9.3)	33 (15.1)	22 (4.9)	14 (10.6)
	Switching cost	18 (8.9)	36 (9.5)	19 (10.6)	38 (9.9)
Mandarin- English ($n = 17$)	Single	489 (10.9)	510 (25.9)	481 (11.6)	534 (32.1)
	Repeat	577 (29.8)	568 (42.0)	563 (18.7)	561 (28.8)
	Switch	612 (27.0)	600 (43.1)	629 (28.5)	591 (34.8)
	Mixing cost	88 (27.5)	58 (23.9)	82 (16.1)	27 (21.8)
	Switching cost	35 (7.4)	32 (23.4)	66 (14.0)	30 (14.4)
Spanish-English ($n = 56$)	Single	537 (6.5)	522 (7.8)	525 (13.0)	523 (7.3)
	Repeat	606 (22.6)	585 (13.1)	596 (21.4)	569 (10.9)
	Switch	635 (25.5)	619 (19.2)	609 (20.9)	605 (13.9)
	Mixing cost	69 (13.5)	63 (10.0)	71 (12.9)	45 (7.8)
	Switching cost	29 (6.4)	35 (9.6)	13 (8.9)	37 (8.8)

Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

Mean RT (SEM) for the colour and shape tasks as training and as transfer task, by language group

		Colour		*Shape*	
		Training1	*Transfer*	*Training1*	*Transfer*
Monolinguals ($n = 54$)	Single	511 (14.2)	522 (17.2)	471 (13.4)	487 (13.4)
	Repeat	593 (15.7)	611 (22.3)	561 (15.4)	599 (23.2)
	Switch	609 (18.2)	650 (27.3)	606 (18.0)	654 (29.4)
	Mixing cost	82 (9.6)	89 (10.0)	89 (10.9)	112 (14.1)
	Switching cost	16 (9.5)	40 (11.4)	45 (10.8)	55 (16.9)
Hebrew- English ($n = 31$)	Single	463 (18.2)	491 (17.2)	531 (21.1)	545 (14.8)
	Repeat	529 (24.6)	544 (24.2)	603 (21.3)	620 (32.1)
	Switch	559 (22.7)	573 (30.0)	658 (27.1)	652 (32.2)
	Mixing cost	66 (13.9)	52 (18.1)	72 (18.0)	75 (24.3)
	Switching cost	30 (10.3)	29 (13.2)	55 (23.2)	31 (14.7)
Mandarin-English ($n = 17$)	Single	542 (24.5)	543 (17.4)	522 (30.8)	514 (17.4)
	Repeat	592 (20.6)	652 (36.6)	594 (30.1)	652 (42.8)
	Switch	613 (29.5)	691 (33.3)	653 (42.7)	738 (45.1)
	Mixing cost	50 (18.0)	109 (27.7)	72 (9.9)	138 (30.9)
	Switching cost	21 (18.1)	40 (14.8)	59 (23.4)	87 (20.1)
Spanish- English ($n = 56$)	Single	570 (12.3)	586 (15.9)	563 (15.5)	573 (13.5)
	Repeat	674 (17.2)	681 (23.2)	648 (16.4)	679 (19.3)
	Switch	678 (21.8)	698 (24.7)	700 (20.2)	727 (22.8)
	Mixing cost	103 (12.3)	95 (11.5)	85 (12.5)	106 (12.7)
	Switching cost	4 (12.1)	16 (13.3)	52 (11.6)	49 (13.1)

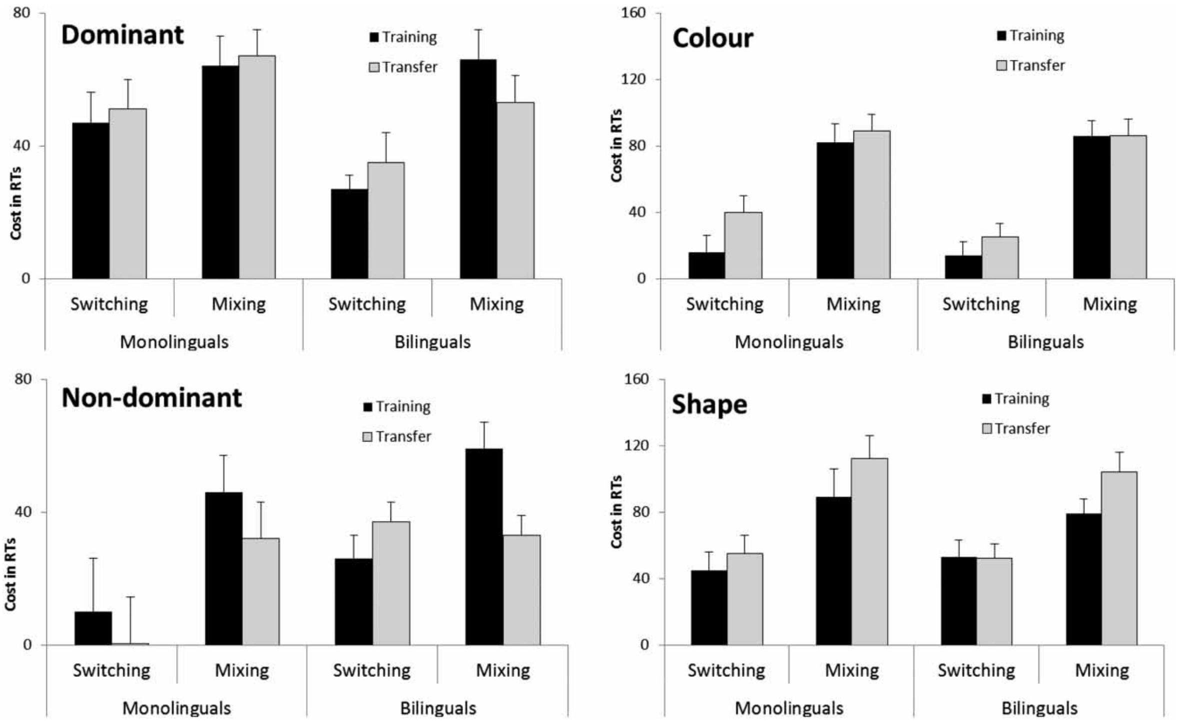

Figure 2. Transfer effects in switching and mixing costs in RTs for bilinguals and monolinguals in all four tasks. Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

Exploratory search for relationships between tasks

Having found limited evidence of transfer between tasks, we asked whether we could find any other indication of a relationship between linguistic and non-linguistic control. Our chosen design required participants to perform both linguistic and non-linguistic control tasks, thus allowing us to look for similarities between domains in three additional ways. First, adopting an individual differences approach, we asked whether performance was correlated across linguistic and non-linguistic switching tasks, focusing on the switching costs and mixing costs. In these analyses, we asked whether participants who are relatively facile at switching between languages also shift more efficiently between non-linguistic tasks, and whether these relations were different for bilinguals and monolinguals. Similarly, we asked whether the susceptibility to interference and intrusion errors (responding in the non-target language or to the non-target task) was correlated across linguistic and non-linguistic task switching (Festman et al., 2010; Gollan et al., 2011). Finally, adopting a framework recently described by Calabria et al. (2012), we asked if the pattern of switching and mixing costs was similar across tasks with respect to symmetry in task dominance. All analyses in this section were performed on the Training1 and Transfer sequences, to avoid practice effects on the Training task.

Correlations of costs between tasks. We first examined possible correlations between the switching costs and mixing costs in the two tasks. To this end we calculated for each participant the two cost types for his or her first encounter with each task (language and colour/shape), collapsing across the day of testing. Thus, as noted above, we analysed language-switching costs for participants who performed this task as the Training1 sequence jointly with the language-switching costs of participants who performed this task as the Transfer sequence. When examining all participants, we found a significant correlation between colour/shape-switching costs and language-switching costs ($r(158) = .19$, $p < .05$), and a stronger association between mixing costs in the two paradigms ($r(158) = .39$, $p < .01$). In both cases we also examined these correlations separately for bilinguals and monolinguals. For monolinguals, the correlation between switching costs was significant ($r(54) = .44$, $p < .01$) but the cor-

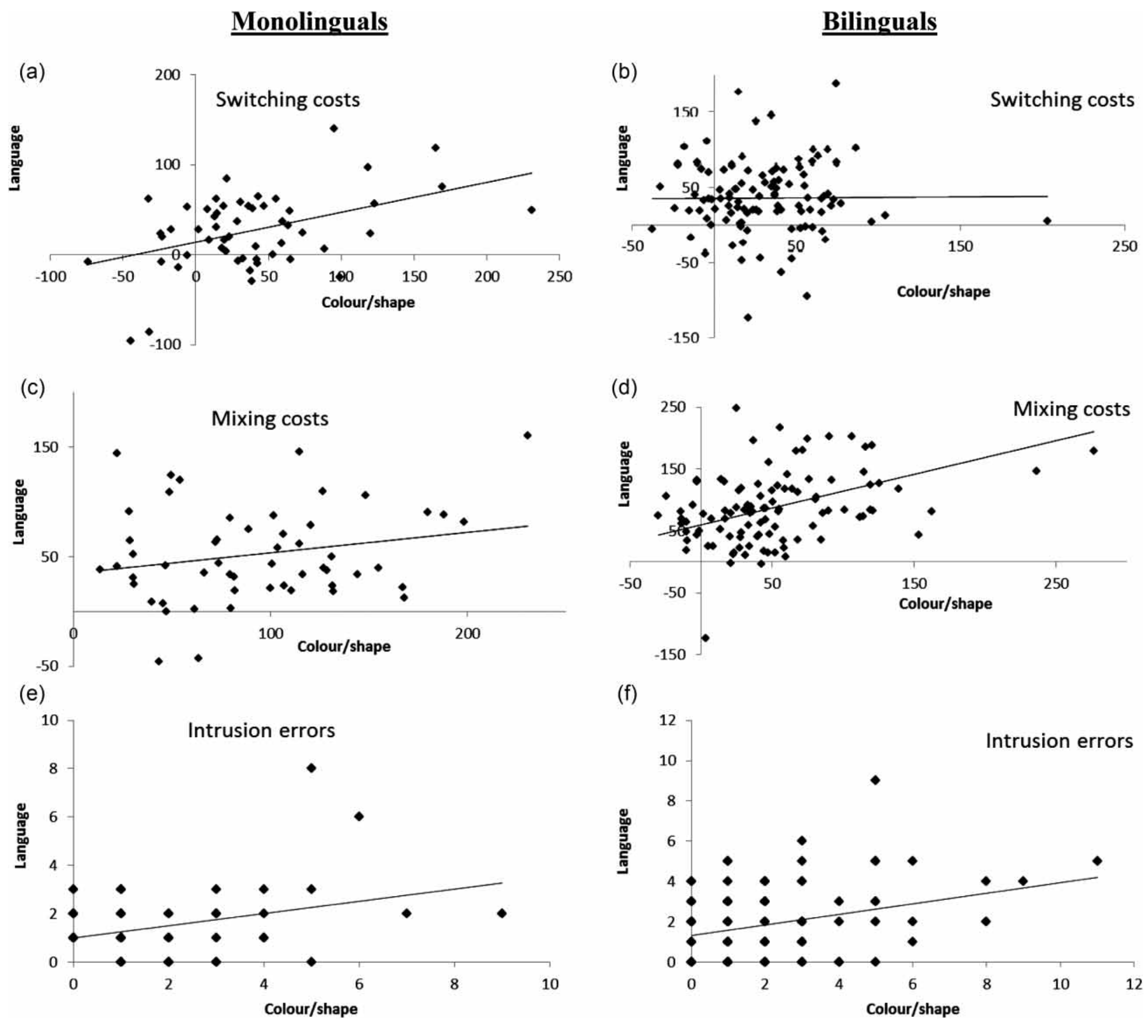

Figure 3. Correlations across language and non-linguistic switching in switching costs (panel a, monolinguals; panel b, bilinguals), mixing costs (panel c, monolinguals; panel d, bilinguals) and intrusion errors (panel e, monolinguals; panel f, bilinguals). Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

relation between mixing costs was not ($r(54) = .22$, $p = .11$). However, bilinguals exhibited the opposite pattern; for bilinguals, the correlation between switching costs was not significant ($r(104) = .01$, $p = .92$), but the correlation between the mixing costs was statistically robust ($r(104) = .45$, $p < .01$). These patterns are illustrated in Figure 3.[1]

Correlation of intrusion errors between tasks. In both tasks, intrusions were coded when speakers failed to perform the task indicated by the cue (i.e., responding in the wrong language in the language task, and judging by the wrong dimension in the colour/shape task). Because intrusions were extremely rare in the single-language and single-task blocks, we analysed intrusion rates only from the mixed blocks, collapsing across repeat and switching trials. Note that a majority of intrusion errors in both the language task (75%)

[1] Note that exclusion of outliers did not change these patterns substantially. When we eliminated the highest and lowest observation for each cost type for each participant group, the correlation in mixing costs for the entire sample was reduced somewhat but remained significant ($r(152) = .24$, $p < .01$). A comparison of the two language groups again yielded a significant correlation for bilinguals ($r(101) = .31$, $p < .01$) but not for monolinguals ($r(51) = .03$, $p = .81$). The general correlation in switching costs was also somewhat reduced ($r(150) = .12$, $p = .13$) and was no longer significant in the entire sample. However, after separating the two language groups, the correlation remained significant for the monolinguals ($r(50) = .36$, $p < .01$) but not for the bilinguals ($r(100) = -.03$, $p = .75$. Eliminating the outliers in the analysis of intrusion errors again somewhat reduced the magnitude of the correlation ($r(150) = .24$, $p < .01$), but it remained significant.

and the colour/shape task (64%) occurred during switching trials. An analysis including all four participant groups showed a significant correlation ($r(154) = .32$, $p < .01$); participants who produced more intrusion errors in the language task also tended to make more intrusion errors in the colour/shape task. In this case, the correlation was significant for both monolinguals ($p < .05$) and bilinguals ($p < .01$; see Figure 3).

Symmetric or asymmetric costs. In previous studies, balanced bilinguals have sometimes exhibited symmetric switching costs in studies of cued language switching (e.g., Costa & Santesteban, 2004), whereas unbalanced bilinguals exhibited asymmetric switching costs, following a pattern frequently reported in the task-switching literature, such that the dominant task or language exhibits greater switching costs than the non-dominant task or language (Kiesel et al., 2010; Meuter & Allport, 1999; Monsell, 2003). Calabria et al. (2012) reasoned that if control mechanisms are fully shared across linguistic and non-linguistic tasks, then the pattern of switching costs should be symmetric in both domains for balanced bilinguals. However, they did not confirm these predictions; specifically, they reported symmetric language-switching costs, but asymmetric switching costs in a colour/shape paradigm similar to the one used in the current study (i.e., larger switching costs for the colour task than the shape task). In addition, they failed to find significant correlations in switching costs between tasks (as we reported above), and on these bases concluded that language control relies on mechanisms that are separate from general cognitive control.

However, as noted above, it is difficult to draw definitive conclusions from a failure to find correlations. The current data set allows us to revisit and expand on these findings in several ways. First, in our study, participants spoke their responses in both the linguistic and the non-linguistic tasks, and the two tasks were structured in exactly the same way, whereas Calabria et al. (2012) used a spoken-language-switching task and a manual sort-to-match version of the colour/shape task, thereby artificially introducing some limitations on similarities across tasks. Additionally, our inclusion of single-task blocks (and MINT scores) provides a cleaner assessment of task and language dominance (Calabria et al., 2012 examined performance only in mixed-task blocks) and makes it possible to test the predictions of interest with both switching and mixing costs, thereby examining two different aspects of executive control (Kray & Lindenberger, 2000; Rubin & Meiran, 2005). Finally, we tested four participant groups in the present study; thus, with four groups, and both switching and mixing costs, together this provided eight independent retests of the questions asked by Calabria et al. (2012).

Figure 4 shows the means for these comparisons, and Table 6 summarises the results of the analyses which were carried out as follows. The first two columns show the dominance patterns for each task by language group. Following Weissberger et al. (2012), in these comparisons we compared RTs for the two tasks (colour and shape) and for the two languages in the single-task blocks, and language dominance was assigned based on MINT scores. Monolinguals and Hebrew-English bilinguals exhibited language dominance effects—they were faster in the dominant language than in non-dominant one, whereas the Spanish-English and Mandarin-English bilinguals exhibited a more balanced bilingual profile. In the colour/shape task, Hebrew-English bilinguals were faster on the colour task, monolinguals and Mandarin-English bilinguals were faster on the shape task, and Spanish-English bilinguals did not show a statistically significant difference between the tasks, though they too were faster on the shape task. It is not clear why dominance patterns were different across groups—Hebrew-English bilinguals might have been affected by responding in Hebrew (rather than English, like the other three groups), but this cannot explain the differences between the Spanish-English bilinguals and the other two groups tested in San Diego.

Setting group differences in dominance patterns aside, given the pattern of dominance effects we obtained, we would expect asymmetric costs for language switching in Hebrew-English bilinguals and in monolinguals (because they exhibited language dominance effects), but symmetric costs for language switching in the Spanish-English and Mandarin-English bilinguals. Further, we would expect asymmetric costs for the colour/shape task for all participants except the Spanish-English bilinguals. The remaining four columns to the right indicate whether costs were symmetric or asymmetric. We compared switching and mixing costs across languages and tasks using paired t-tests. In Table 6, pairs in which the costs exhibit the same pattern (either symmetric or asymmetric) across both tasks are shaded grey. As can be seen

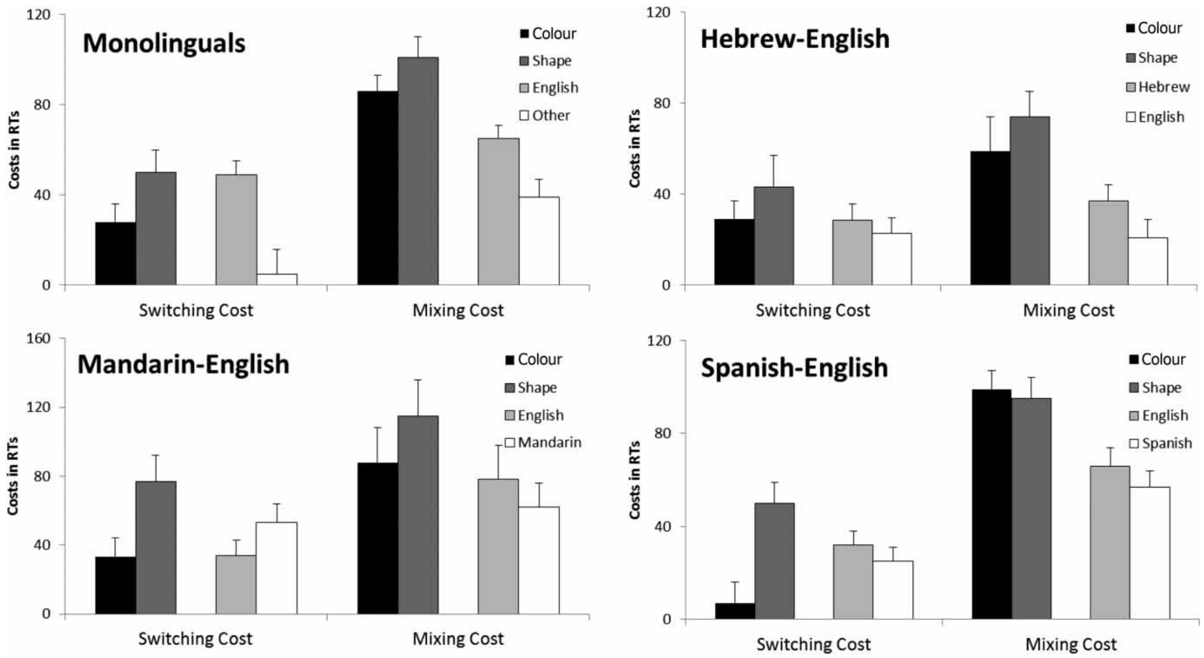

Figure 4. Switching and mixing costs for both tasks, by participant group. Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

TABLE 6
Patterns of switching and mixing costs across tasks, by language group

	Language dominance (single blocks)	*Task dominance (single blocks)*	*Language switching cost pattern*	*Colour/shape switching cost pattern*	*Language mixing cost pattern*	*Colour/shape mixing cost pattern*
Monolinguals	Yes: faster in dom. Language ($p < .01$)	Yes: faster on shape ($p < .01$)	Asymmetric smaller for non-dom ($p < .01$)	Asymmetric smaller for colour ($p < .05$)	Asymmetric smaller for non-dom ($p < .01$)	Marginal asymmetric smaller for colour ($p = .06$)
Hebrew- English	Yes: faster in dom. Language ($p < .01$)	Yes: faster on colour ($p < .01$)	Symmetric ($p = .89$)	Symmetric ($p = .42$)	Asymmetric smaller for non-dom ($p < .01$)	Symmetric ($p = .34$)
Mandarin-English	No ($p = .61$)	Yes: faster on shape ($p < .05$)	Symmetric ($p = .14$)	Asymmetric smaller for colour ($p < .05$)	Symmetric ($p = .31$)	Asymmetric smaller for colour ($p < .05$)
Spanish- English	No ($p = .24$)	No ($p = .18$)	Symmetric ($p = .34$)	Asymmetric smaller for colour ($p < .01$)	Symmetric ($p = .18$)	Symmetric ($p = .53$)

Cells in grey are cases where the pattern of costs is matched across the language- and the colour/shape-switching tasks. Note that for monolinguals, the non-dominant other language consisted of foreign-language number words.

in Table 6, the pattern of costs was equally often parallel or divergent across tasks (2 out of 4 cases for switching costs, and 2 out of 4 cases for mixing costs). In addition, asymmetric costs were not always associated with task-dominance effects (e.g., Hebrew-English bilinguals had clear language dominance in the single blocks, but nonetheless exhibited symmetric language-switching costs). Thus, these analyses imply that there are both similarities and differences across tasks in the pattern of costs reported, and at the same time demonstrate that symmetry/asymmetry are not the hallmark of balanced/unbalanced performance within switching paradigms (e.g., see also Christoffels, Firk, & Schiller, 2007; Gollan & Ferreira, 2009).

DISCUSSION

The current study was designed to investigate relationships between language switching and non-linguistic-task switching. In the non-linguistic colour/shape task, performance improved significantly with practice on the first day of training, particularly for the mixed-task blocks, leading to a reduction in mixing costs. However, within the mixed blocks themselves, performance improved to the same degree on both repeat and switching trials, thus switching costs were not reduced with training. These observed training gains for the colour/shape task persisted on the second day of testing, for which performance was as fast as it had been at the end of practice on Day 1. On the other hand, training effects in the language task were only observed for the non-dominant language for monolinguals. Because for these participants the non-dominant language was not fully functional and rarely used, some degree of this improvement might be attributable to the simple repetition of the actual numeric labels within the context of the experiment. In contrast, for all bilingual participants, language performance appeared to be close to ceiling levels of performance from the very first training sequence, and showed no improvement with training (though bilinguals and monolinguals exhibited some transfer effects—as discussed below).

Though the colour/shape task exhibited robust training effects, there were no significant cross-task transfer facilitation effects for this task. Instead, there was a trend in the opposite direction for the shape task—namely, participants who first practised the language-switching task exhibited *larger* mixing costs for the shape task than those who performed it on the first day of training. Significant transfer facilitation effects were found only for the non-dominant language—mixing costs were smaller for participants who performed the language task after practising the colour/shape task than for participants who performed the language-switching task first.

We also observed some small but significant relationships between tasks in two subsequent analyses including (a) some limited cross-task training transfer facilitation effects from colour/shape training to mixing costs in the non-dominant language, and (b) significant between-task correlations (see Figure 3). Most notably, bilingual participants who mixed languages efficiently also mixed non-linguistic tasks efficiently, and monolingual participants who incurred smaller switching costs for the non-linguistic task also incurred smaller costs in language switching. Similarly, intrusion errors in the mixed blocks were correlated across tasks, such that participants who were accurate in responding to language cues were also accurate in responding to colour/shape cues.

A final series of analyses produced mixed results, demonstrating that the pattern of switching and mixing costs, either symmetric or asymmetric, was matched in half the comparisons (see Figure 4 and Table 6) across the linguistic and non-linguistic paradigms. The patterns of symmetry or asymmetry differed across the participant groups. In particular, the monolinguals and the late Hebrew-English bilinguals exhibited some cost asymmetries consistent with previously reported findings that the dominant language pays a higher price for language switching than the non-dominant language (Meuter & Allport, 1999). In this case, monolinguals had asymmetric costs for both language mixing and language switching, whereas the Hebrew-English bilinguals showed an asymmetry for language mixing costs but not for switching costs. As far as the correspondence in patterns of symmetry across linguistic and non-linguistic tasks, our results only partly overlap with those reported by Calabria et al. (2012), as in half the cases we do find a convergence in the patterns of costs (switching or mixing) across the paradigms. It would seem important to establish more specifically the factors that lead to symmetric versus asymmetric costs, or even fully reversed language dominance, as has sometimes been found in both cued and voluntary switching paradigms (e.g., Costa & Santesteban, 2004; Gollan & Ferreira, 2009), before attempting to draw firm conclusions from either associations (or a lack thereof; see Calabria et al., 2012) in the pattern of costs observed across linguistic and non-linguistic paradigms.

Two main questions arise when considering the results reported above. First, why did we fail to observe transfer facilitation for the colour/shape task, which exhibited robust within-task training effects? The conclusions that can be drawn from a failure to observe transfer effects are necessarily limited, but could suggest that the degree of overlap between linguistic and non-linguistic control is rather small. Consistent with this conclusion, the correlations we observed between tasks, though statistically robust, were also rather small (between .30 and .45; see Figure 3). It is possible that cross-task transfer could be observed with more extensive training (e.g., Karbach & Kray, 2009), or with more immediate testing (rather than after a week's delay). Indeed, recent reviews of the cognitive training literature might suggest that such improvements on the training regime might have led to more robust training effects (Hussey & Novick, 2012; Shipstead, Redick, & Engle, 2012). Interestingly, however, most of the work in this domain has focused on training to improve working memory capacity, and there is less evidence regarding specific training of cognitive flexibility using task-switching paradigms (but see Karbach & Kray, 2009). As this is the first study to examine possible transfer effects between linguistic and non-linguistic switching, future research should examine more closely possible parameters that might result in more robust training. Further, recent theoretical approaches underscore the importance of executive control function for language processing in both bilinguals and monolinguals (Hussey & Novick, 2012). Thus, further developments along these lines may ultimately help to clarify any unique roles for executive control more specifically in the domain of bilingual language production.

The fact that the present study included bilinguals of varying proficiency levels and acquisition histories, as well as monolinguals, suggests that the results we reported (limited transfer, and limited correlations between linguistic and non-linguistic domains) should apply quite broadly (e.g., if we had tested only bilinguals with a lifetime of experience with switching languages this might have limited substantially the extent to which additional practice could further improve and transfer to non-linguistic switching). These findings suggest that the current results might indeed generalise broadly to a variety of bilingual types, a non-trivial conclusion in light of the growing interest in the variability in bilingual experiences and circumstances, and their possible importance for investigating the link between bilingualism and cognitive control (Green, 2011; Prior & Gollan, 2011; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011).

A second question concerns the above-reported finding of significant correlations between tasks in mixing costs for bilinguals, but correlations between domains in switching costs only for monolinguals. This seems unexpected, given previous reports that bilingualism reduces switching but not mixing costs in non-linguistic task switching,[2] but fits with recent suggestions that mixing (not switching) improves with expertise (Weissberger et al., 2012). Further, the limited transfer that we found in the current design was again a reduction in mixing costs, but not switching costs (for the non-dominant language), and even training effects where these were observed after a one-week delay were robust in mixing costs but not in switching costs in the colour task. These findings of similarities in mixing costs for the two tasks dovetail nicely with some recently proposed explanations for the bilingual advantage in executive control. Mixing costs arguably reflect mostly global or sustained control processes, and several researchers have identified these processes exactly as the locus of bilingual advantages (see Bialystok et al., 2009 for a review). Thus, Costa et al. (2009) have suggested that bilingual-

[2] The present study allowed us to probe whether the previously reported switching-cost advantage in non-linguistic switching for bilinguals (Prior & MacWhinney, 2010; Prior & Gollan, 2011) was replicated in the current data set, because it included the same participant groups as tested by Prior and Gollan (2011).In our previous study (Prior & Gollan, 2011), Spanish-English, but not Mandarin-English, bilinguals exhibited significantly smaller switching costs than monolinguals in the colour/shape task, and the advantage was present only after controlling for between-group differences in socio-economic status (SES) (parent education level). In addition, Spanish-English bilinguals exhibited significantly smaller switching costs than Mandarin-English bilinguals in both linguistic and non-linguistic tasks, a finding we linked to the fact that Spanish-English bilinguals reported switching languages more often in daily life. In the current data set, the Spanish-English bilinguals reported switching languages about as often as Spanish-English bilinguals in the 2011 paper (3.4, see Table 1 in this paper, versus 3.2 on the same five-point scale in Prior & Gollan, 2011).To replicate the analysis reported in Prior & Gollan (2011), we looked at RTs from the Training1 and Transfer sequences and calculated the relative switching cost for each individual in the colour/shape task, and also corrected for group differences in SES by including parental education as a covariate in the analysis. To that end we divided the switching cost (the difference between switching and repeat times) by the mean RT on repeat trials. This relative switching cost was calculated to correct for the slower response times of the bilinguals. In an ANCOVA on the relative switching cost, with primary caregiver education entered as a covariate, we did not find an effect of language group ($F < 1$).A key consideration in interpreting this failure to replicate is that in the current study bilinguals produced vocal responses in the colour/shape task, whereas previous studies relied on manual responses. Well-documented bilingual disadvantages in verbal responses might have masked switching-cost advantages in the current data, and indeed the Spanish-English and Mandarin-English bilinguals were significantly slower than monolinguals in overall response speed in the colour/shape task ($p < .001$).

ism might lead to enhanced monitoring capacities, based on speeded responses only under conditions of heightened uncertainty. Similarly, Hilchey and Klein (2011) have recently argued that the finding of reduced response times for bilinguals across both conflict and non-conflict trials in Stroop- and flanker-type paradigms also point towards a generalised executive advantage for bilingualism, which has some similarities to the monitoring account put forth by Costa et al. (2009); but see also Prior, 2012). This aspect of our results supports these notions; the practice that bilinguals gain in managing languages in their daily life might confer on them sharper general executive abilities. Additionally, although we found correlations between tasks in switching costs for monolinguals only, we did find significant correlations between mixing costs for bilinguals and correlations across tasks in intrusion errors for all participants. These findings could suggest that bilingual advantages are driven by processes that bilinguals develop to allow them to mix languages, and to prevent language-selection errors, and not as much by processes related to rapidly planning and executing a language switch.

Taken together, the results of the current study echo recent observations of relationships between bilingual language use and executive control abilities while also demonstrating some inherent limitations therein, and illustrating robust differences between the tasks under investigation. The finding of such limited cross-task similarities seems surprising given that in the present study the tasks were matched as closely as possible methodologically—both employed the same types and sequences of trials, and were matched for response modality. Curiously, where we did observe a cross-task transfer effect, this was only for the non-dominant language, not for the colour/shape task as we had expected to see based on previously reported bilingual advantages. Similarly, where we did observe significant relationships between linguistic and non-linguistic switching, and significant transfer and training effects, this was in mixing costs, and again not in switching costs as might have been expected given previously reported bilingual advantages in switching. These findings suggest caution against the practice of comparing bilinguals to monolinguals in the hopes of revealing relationships between linguistic and non-linguistic control, and suggest that a more fruitful line of research will be to directly compare tasks (as done here), or at least that both types of approaches will be needed in order to arrive at a comprehensive understanding of this issue. The current data imply that a promising avenue to explore in future work is in how bilinguals prevent language-selection errors. Here it may be useful to consider that the majority of intrusion errors that occur in switching paradigms entail failures to switch in response to the cue on switching trials; however, very little is known about failures to switch in natural language use. Indeed there are only a few investigations of naturally occurring language-intrusion errors (Gollan et al., 2011; Poulisse, 1999), and these involve errors of a very different nature, that is, unintended language switches, which are relatively rare in switching paradigms. This distinction may provide an important thread to follow in future investigations.

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