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Non-linguistic effects of language switching training

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Abstract

What is the relationship between bilingual language control (BLC) mechanisms and domain-general executive control (EC) processes? Do these two domains share some of their mechanisms? Here, we take a novel approach to this question, investigating whether short-term language switching training improves non-linguistic task switching performance. Two groups of bilinguals were assigned to two different protocols; one group was trained in language switching (switching-task training group) another group was trained in blocked language picture naming (single-block training group). Both groups performed a non-linguistic and linguistic switching task before (pre-training) and after training (post-training). Non-linguistic and linguistic switch costs decreased to a greater extent for the switching-task training than for the single-block training group from pre- to post-training. In contrast, mixing costs showed similar reductions for both groups. This suggests short-term language switching training can transfer to the non-linguistic domain for certain sub-mechanisms (i.e., switch cost). Thus, there is some overlap of the control mechanisms across domains.

Keywords: bilingual language control, executive control, training effects, transfer

1 Introduction

The extent to which bilingual language control (BLC) and domain-general executive control (EC) processes share some of their mechanisms is a debated issue (Abutalebi & Green, 2007; Declerck, Koch, & Philipp, 2015; Dijkstra & van Heuven, 2002; Grainger, Midgley, & Holcomb, 2010; Green, 1998). This question is relevant when trying to understand whether BLC mechanisms are an instantiation of domain-general EC processes. The experimental evidence used to inform this issue comes from several sources. One of the most common paradigms used in the question regarding cross-talk is the comparison (either behaviorally or through neuroimaging studies) of a bilingual's performances in linguistic and non-linguistic control tasks (Branzi, Calabria, Boscarino, & Costa, 2016; De Baene, Duyck, Brass, & Carreiras, 2015; Timmer, Calabria, Branzi, Baus, & Costa, 2018; Timmer, Grundy, & Bialystok, 2017a). Here, we take a novel approach and explore cross-talk between BLC and EC by assessing whether short-term training in BLC affects performance on tasks that involve EC but do not (or only minimally) involve linguistic processes (Abutalebi et al., 2008; Dijkstra & van Heuven, 2002; Green, 1998).

The evidence regarding cross-talk that comes from correlational studies is based on the idea that if the two domains share cognitive processes then individuals' performances in tasks that involve linguistic and non-linguistic control should correlate to some extent. To put it simply, if BLC is subsumed to EC processes, those individuals that are good at the latter should be good at the former too. This hypothesis has been tested mostly by looking at switching tasks (linguistic switching vs. non-linguistic switching tasks). Given that we also used these tasks in the present study, the following review will be focused on these types of studies. Most of the correlational studies do not reveal a correlation between switching costs across the linguistic- and non-linguistic tasks (Branzi et al., 2016; Calabria, Branzi, Marne, Hernández, & Costa, 2015; Calabria, Hernández, Branzi, & Costa, 2011; Cattaneo et al., 2015; Declerck, Grainger, Koch, & Philipp, 2017; Prior & Gollan, 2013). However, some studies revealed a correlation for the switch cost across domains (Declerck et al., 2017; Timmer, Calabria, et al., 2018) or for the mixing cost across domains (Cattaneo et al., 2015; Prior & Gollan, 2013).

Moreover, other studies have looked at whether performances in task switching varied depending on the frequency of language switching in real life. The results of these studies suggest that more frequent language switching in daily life improves non-linguistic task switching performance (Hartanto & Yang, 2016; Pot, Keijzer, & de Bot, 2018; Prior & Gollan, 2011; Soveri, Rodriguez-Fornells, & Laine, 2011; Yang, Hartanto, & Yang, 2016). For example, Hartanto and Yang (2016) showed diminished switch costs in a non-linguistic task for those participants who used both languages within the same context (dual-language context) compared to bilinguals who only speak one language in a specific environment (single-language context) (for a similar study but opposite results see Jylkkä et al., 2017). This suggests that the language context a bilingual resides in matters to some extent. Indeed, bilinguals that switch between their languages more frequently seem to engage control mechanisms to a different extent (the adaptive control hypothesis, Green & Abutalebi, 2013). Hence, these observations suggest that training in BLC may affect performance in domain-general EC tasks, a hypothesis tested in our study, however, clear attention needs to be paid to the type of context bilinguals are in.[1]

Along with behavioral data, neural data has also been investigated for the presence of cross-talk between BLC and EC. Imaging results show a greater recruitment of BLC areas when performing a non-linguistic switching task for bilinguals than monolinguals (Garbin et

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[1] A different but related topic are studies that show that intensive second language learning has a positive impact on domain-general attentional control (Bak, Long, Vega-Mendoza, & Sorace, 2016) and cognitive decline (Antoniou, Gunasekera, & Wong, 2013) as language learning engages an extensive network of the brain and is cognitively stimulating.

al., 2010; Rodríguez-Pujadas et al., 2013). However, studies that compared brain activity in linguistic versus non-linguistic switching tasks directly in the same bilingual speakers suggest that there is only partial overlap across the domains (De Baene et al., 2015; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015). Some degree of overlap between both switching tasks has been found over prefrontal/frontal areas (lateral and medial) and the parietal lobule (inferior and superior) (De Baene et al., 2015). However, Weissberger and colleagues (2015) found that activation for the non-linguistic task was more widespread than for the language task and dependent on type of trials (switch or repeat). Moreover, an electrophysiological (EEG) study demonstrated that for the switch cost the scalp distributions showed overlap between task switching and language switching for the P3/LPC (Latent Positive Component), but not for the N2 (Timmer et al., 2017a). In sum, the current evidence of a common neural network of the BLC and the EC system does not seem to support a complete overlap.

Here we take a novel approach and assess whether training in a task that involves BLC has an impact on participants' performance on an EC task that does not involve language control. To assess this issue, we compare participants' performances on an EC task before and after they conduct a language training task. There were two different training groups: one group performed a language switching training that required BLC (switching-task training group), while the other group performed a language task without the need for BLC (single-block training group). We hypothesize that if BLC and EC share some processes then training in the former domain should lead to some benefits in the latter domain. In fact, the two training protocols could be argued to parallel, to some degree, the two different language contexts described in the adaptive control hypothesis (Green & Abutalebi, 2013). Language switching training (switching-task training group) resembles the dual-language context in which switching between languages occurs, while the blocked language protocol (single-block training group) resembles the single-language context in which each language is used in a different environment. That is, we investigate if EC is differentially modulated depending on the type of short-term language context/training.

The transfer approach used in the present study has already been applied to study the sub-components of EC. For example, non-linguistic task switching training revealed not only improvement on the same task (Buchler, Hoyer, & Cerella, 2008; Karbach & Kray, 2009; Kramer, Hahn, & Gopher, 1999; Kray, Eber, & Karbach, 2008; Minear & Shah, 2008; Zinke, Einert, Pfennig, & Kliegel, 2012), but also improved performance in other tasks and domains of EC (Karbach & Kray, 2009; Kray, Karbach, Haenig, & Freitag, 2012; Zinke et al., 2012). In the context of bilingualism, there is evidence that language switching performance improves with training in the same task (Kang et al., 2017; Kang, Ma, & Guo, 2018; Wu et al., 2018). They found that the language switch cost decreased from pre- to post-test after 8 days of training on language switching, but only when the stimuli at post-test were the same as at pre-test. Moreover, the brain data reveals more efficient processing on the N2 component (Kang et al., 2018) or over the ACC, the neural generator of the N2 (Kang et al., 2017). However, as of yet there is no evidence that language switching training transfers to the EC domain (Prior & Gollan, 2013). One group performed a language task, that included both pure blocks, with only one language, and mixed blocks, with two languages. After a week they performed a non-linguistic task, which did not show improved EC performance. These results led the authors to conclude that the link between the two domains of control is elusive.

In the present study, we investigated the difference between the effect of language switching and blocked language naming on a non-linguistic task with a between group design and we pay attention to two indexes of control, namely switch and mixing costs. These indexes, present in both linguistic and non-linguistic switching tasks (for reviews see Bobb & Wodniecka, 2013 and Meiran, 2010), are assumed to capture two different types of control, reactive and proactive respectively (Braver, Reynolds, & Donaldson, 2003). The switch cost is calculated by subtracting performance in repeat trials from switch trials. The mixing cost is calculated by comparing performance in repeat trials to the switching task and trials in blocks that involve just one task (or language); the so called ‘pure blocks’. Within the task switching literature switch costs are understood to reveal both the cost associated with retrieving the rules associated with a signaling cue from memory and the need to reconfigure the appropriate stimulus-response mappings for the task at hand (Hernández, Martin, Barceló, & Costa, 2013; Jost, Mayr, & Rosler, 2008; Meiran, 2010; Prior & Macwhinney, 2010). There are similar explanations of switch costs observed in language tasks (Costa, Miozzo, & Caramazza, 1999; Green, 1998; La Heij, 2005; Roelofs, 1998; Timmer, Christoffels, & Costa, 2018). The switch cost has also been understood to index a transient type of control that resolves interference when it is detected in a trial by trial fashion. In contrast, mixing cost has been suggested to involve a more sustained type of control that maintains a task goal active, promotes cognitive flexibility, and facilitates the processing of possible upcoming conflicts (Braver et al., 2003). Similarly, proactive control has been related to the ability of maintaining the two languages active (Cattaneo et al., 2015; Ma, Li, & Guo, 2016).

In our study we asked two groups of participants to perform a non-linguistic switching task in two sessions (pre-training and post-training, about a week apart). Between these sessions two training sessions were included. The first training session immediately followed the pre-training task and the second training session immediately preceded the post-training task, that was performed a week after the pre-training and first training session. One group of participants performed a linguistic switching task involving two languages (switching-task training group), and hence engaging BLC as in dual-language contexts (Green & Abutalebi, 2013). The other group of participants (single-block training group) performed a blocked naming task in just one language, and hence they did not switch between languages simulating a single language context. Arguably, this language blocked naming task, recruits BLC processes to a much lesser extent than the language switching task.

By comparing participants' performance for the switching-task training group in the pre- and post-training sessions, we can assess the potential effect of BLC training on the reactive (i.e., switch cost) and proactive (i.e., mixing cost) domain-general EC processes. Specifically, we expected a greater decrease of the switch cost from pre- to post-training for the switching-task training compared to the single-block training group. The switching-task training group trained specifically on reactive language control mechanisms of BLC during language switching, while the single-block training group did not train on these reactive control mechanisms. To the extent that the switch cost indexes processes that are shared by BLC and EC systems they should be affected more by the linguistic-switching training than the single-block training. Further, we expected similar improvement in the mixing cost for both groups as this cost is indexed by a more general type of control that balances the activation of two languages by a global and proactive type of control. Both training groups have the need for this global control.

Finally, the pre- and post-training sessions also included a language-switching task. This was included to investigate the post-effects of training on the language control and to see to which extent the non-linguistic and linguistic control tasks revealed similar effects. This gives us the opportunity to further investigate the similarities between the non-linguistic and the linguistic task and to what extent cross-talk is present across domains. For this task we have similar predictions to those of the non-linguistic task. Thus, the switching-task training group should improve to a greater extent from pre- to post-training on the switch cost, but not the mixing cost, in both switching tasks (the full experimental design is schematically represented in Figure 1).

The measurement of this additional task gives us the opportunity to investigate the degree of correlation between the two measures of control (mixing and switch costs) as analyzed in previous studies. We are not sure whether the present study will demonstrate correlations across the two tasks for the switch or the mixing cost as most previous studies have not shown such correlations. The correlational results can be contrasted with the transfer/training results.

2 Method

2.1 Participants

Sixty-eight Catalan-Spanish bilinguals from Universitat Pompeu Fabra were paid for their participation (43 females; average age: 22.0 years; SD = 4.09). They all had normal or corrected-to-normal vision, and no history of neurological impairments or language disorders. They were randomly assigned to the single-block training group (N = 34) or to the switching-task training group (N = 34). Four participants from the single-block training group were excluded, two due to excessively slow responses (> 2.5 SD), one participant on the language switching task and one on the non-linguistic switching task, one due to less than 70% of trials left on the language task after removing errors and voice-keys, one due to technical problems with the PC; and four participants from the switching-task training group: 1 due to technical failure of the voice key, 1 due excessively slow responses (> 2.5 SD) during task-switching, and two due to technical problems with the PC. The final sample was then 30 participants in both the single-block training group (22 females; average age: 22.3 years; SD = 5.22) and the switching-task training group (20 females; average age: 21.5 years; SD = 2.38).

All participants completed a self-rating proficiency and social economic background questionnaire to assess their language experience and proficiency. In addition, all participants completed the Superior Scale I of the Ravens Advanced Progressive Matrices reflecting nonverbal intelligence (Raven, Raven, & Court, 1998). Participants indicated the missing piece of 12 picture items. The eight possible missing pieces were arranged below the picture. The groups were statistically equivalent on age, socioeconomic status, Catalan and Spanish proficiency, and nonverbal intelligence (see Table 1).

		All participants	Single-block training group	Switching-task training group
Catalan	Speaking [a]	5.9 (0.43)	5.9 (0.43)	5.9 (0.43)
	Understanding [a]	6.0 (0.00)	6.0 (0.00)	6.0 (0.00)
	Reading [a]	5.9 (0.49)	5.8 (0.58)	5.9 (0.36)
	Writing [a]	5.7 (0.59)	5.7 (0.64)	5.7 (0.53)
	% using Catalan in a week [b]	68.4 (20.75)	73.3 (19.72)	65.0 (19.62)
Spanish	Speaking [a]	5.5 (0.76)	5.6 (0.62)	5.5 (0.88)
	Understanding [a]	6.0 (0.00)	6.0 (0.00)	6.0 (0.00)
	Reading [a]	6.0 (0.18)	5.9 (0.25)	6.0 (0.00)
	Writing [a]	5.7 (0.52)	5.7 (0.51)	5.7 (0.53)
	% using Spanish in a week [b]	29.6 (19.36)	24.7 (19.45)	35.0 (18.39)
	Education level of the mother [c]	4.1 (1.19)	4.1 (1.11)	4.1 (1.19)
	Education level of the father [c]	3.9 (1.45)	3.9 (1.48)	3.9 (1.39)
	Raven intelligence test score [d]	9.7 (1.68)	9.5 (1.73)	9.8 (1.61)

Table 1. Mean answers (and standard deviations) to self-rating proficiency and social economic background questionnaire.

[a] A 6-point scale, with 1 point being the lowest proficiency and 6 the highest self-rated proficiency.

[b] Percentage out of 100.

[c] A 6-point scale, with 1 point being the lowest and 6 the highest education level.

[d] Raw score out with a maximum score of 12.

2.2 Materials and Procedure

Participants were tested individually in a quiet room with dimmed lights and seated approximately 1 meter from the computer screen. The experiment consisted of two sessions (pre-training and post-training) with approximately a week (5 to 9 days) between sessions. At the first session participants first signed an informed consent form, filled out the language proficiency questionnaire, and completed the Raven's nonverbal intelligence test before the experimental tasks. In between the pre- and post-session two language training sessions were included. The first language training session immediately followed the pre-test and the second language training occurred right before the post-test. See Figure 1 for an overview of the procedure.

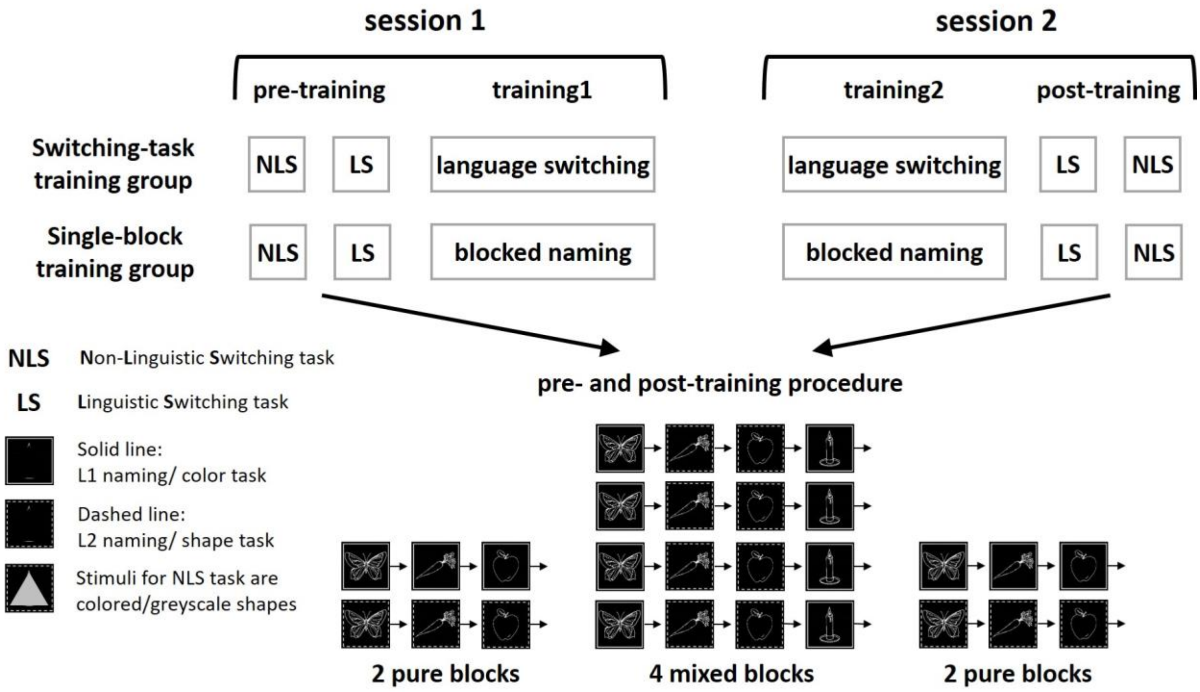


Figure 1. Procedure of the experimental tasks.

2.2.1 Pre- and post-training. In both sessions participants performed a linguistic and a non-linguistic switching task. During the pre-training session, the non-linguistic switching task was followed by a linguistic switching task. During the post-training session, the order was reversed, the linguistic switching task followed by a non-linguistic switching task.

2.2.1.1 Non-linguistic task switching. For the non-linguistic switching task, participants saw colored shapes created from four shapes (square, triangle, circle, and oval) and four colors (red, green, white, and grey). They made decisions about the color (colored or greyscale) or shape (corners or rounded) by pressing the ‘z’ or ‘m’ key for each stimulus (colored shapes). To indicate which decision type (color or shape) was to be performed a cue (solid or dashed outline) appeared around the stimulus. The cue to decision type correspondence was counterbalanced across participants, as was the assignment of keys to a response. Only a subset of the stimuli was presented to each participant so that it would be possible to determine accuracy on each response. For example, a red triangle would not be presented if a participant was responding with ‘z’ for colored (color task) and ‘z’ for corners (shape task). In this case the correct responses for the color and shape task converged on the same keys and no judgment of accuracy could be made. The stimuli were the same as in Timmer and colleagues (2017a).

2.2.1.2 Linguistic task switching. For the linguistic switching task, the stimuli were eight black-and-white line drawings of objects with non-cognate names between Catalan and Spanish (see Appendix A). The line-drawings together with their corresponding names were presented to the participant beforehand so that they knew the intended names for the pictures. The pictures were named in Catalan or Spanish depending on the cue, a solid or dashed outline around the picture. The cue to language correspondence was counterbalanced. The onset of the speech response was measured with a voice key.

2.2.1.3 Procedure of both switching tasks. Both the non-linguistic and linguistic switching task followed the same procedure. Each switching task started with two pure blocks during which only one decision type was performed (non-linguistic task: color or shape; linguistic task: Catalan or Spanish). This was followed by 4 mixed blocks that included both types of decisions. Participants could take short breaks after every block.

Each pure block consisted of 32 trials for a total of 128 pure trials for each participant. The mixed condition consisted of 4 blocks of 48 trials each, for a total of 192 mixed trials. The repeat-to-switch ratio was held at 50% with a total of 96 repeat and 96 switch trials for each participant. An additional trial was added at the beginning of each block (both the pure and mixed blocks). This was because in the mixed blocks the first trial could not be coded as either a switch or repeat. The pure blocks were preceded by 8 practice trials and the mixed blocks by 16 practice trials. Participants were given the opportunity to repeat the practice trials until they felt comfortable enough to move on to the experimental blocks; participants practiced between 1 and 3 times.

For both tasks each trial was initiated by a fixation cross with a duration jittered around 500 ms (400, 500, or 600 ms) followed by the presentation of the target picture together with the cue. The picture remained on the screen until a response was given or after 3000 ms had passed. Only during the practice trials was feedback provided (‘correct’ or ‘incorrect’) for 750 ms. All trials ended with the presentation of a blank screen for 500 ms before the fixation cross was presented again, signaling the start of a new trial.

2.2.2 Language training. In between the pre- and post-task two language training sessions were performed, which were the same. Participants were randomly assigned to the single-block training or switching-task training language training group. The single-block training group named black-and-white line drawings of objects (different from those named during pre-training; see Appendix B) in blocked language sessions (Catalan and Spanish), while the switching-task training group named the line drawings but switched between the two languages within each block.

Just as in the pre- and post-tasks the language training task had 48 trials in each block plus a first trial that was not analyzed. The language training task consisted of 16 blocks both for the first and second training session. A total of 768 trials for each session were analyzed.

Thus, both groups had the same amount of training trials. For the single-block training group each block was named in one language, alternating languages per block. For the switching-task training group the languages were mixed within each block. This led to a total of 384 trials in each Trial type (repeat or switch) for each participant per training session. Before the first block in each language 8 practice trials were presented. For the switching-task training group both languages were used in each block creating repeat and switch trials within each language. Before the first block 16 practice trials were presented. The trial procedure was the same as for the pre- and post-training tasks.

3 Results

Non-linguistic and linguistic switching data were analyzed separately as well as the switch (repeat vs. switch trials) and mixing (pure vs. repeat trials) costs. For the switch cost, the within-subject factors Session (pre-training vs. post- training) and Trial type (repeat vs. switch) and the between-subject factor Group (single-block training group vs. switching-task training group) were examined in a 3-way ANOVA. For the mixing cost the conditions for Trial type were replaced with pure vs. repeat trials. The response latencies and accuracy data are also analyzed separately. Our accuracy data were very high; therefore, the effects should be interpreted with caution. Mean response latencies and accuracy data for pre- and post-training are presented in Table 2 and for the language training in Table 3.

		Pre-training			Post-training					
		Pure blocks	Mixed blocks		Pure blocks	Mixed blocks		Mixing cost		Switch cost	
		Pure	Repeat	Switch	Pure	Repeat	Switch	Pre	Post	Pre	Post
Non-linguistic switching task											
RT (ms)	Single-block training	480 (18.1)	973 (41.6)	1220 (53.4)	424 (11.6)	725 (25.9)	896 (37.6)	493	301	247	171
	Switching-task training	481 (18.1)	904 (41.6)	1153 (53.4)	403 (11.6)	678 (25.9)	789 (37.6)	423	275	249	111
ACC (%)	Single-block training	96.5 (0.34)	98.4 (0.61)	96.4 (0.85)	96.4 (0.39)	98.4 (0.37)	96.0 (0.72)	1.9	2	2	2.4
	Switching-task training	96.4 (0.34)	97.5 (0.61)	96.1 (0.85)	96.2 (0.39)	96.9 (0.37)	95.8 (0.72)	1.1	0.7	1.4	1.1
Linguistic switching task											
RT (ms)	Single-block training	697 (13.1)	871 (23.6)	950 (27.9)	702 (16.5)	827 (26.9)	898 (30.3)	174	125	79	71
	Switching-task training	679 (13.1)	841 (23.6)	921 (27.9)	678 (16.5)	817 (26.9)	850 (30.3)	162	139	80	33
ACC (%)	Single-block training	98.9 (0.31)	97.0 (0.56)	96.7 (0.72)	98.9 (0.24)	96.4 (0.55)	95.6 (0.69)	1.9	2.5	0.3	0.8
	Switching-task training	98.6 (0.31)	96.7 (0.56)	94.5 (0.72)	99.3 (0.24)	97.1 (0.55)	96.6 (0.69)	1.9	2.2	2.2	0.5

Table 2. Mean response latencies in ms (and standard error) and mean accuracy in percentages (and standard error) for non-linguistic task switching and linguistic switching for each condition by Session and Group.

Note: Switching-task training = Switching-task training group; Single-block training = Single-block training group; Mixing cost (repeat – pure); Switch cost (switch – repeat).

		Training session 1			Training session 2		
		Pure blocks	Mixed blocks		Pure blocks	Mixed blocks	
		Pure	Repeat	Switch	Pure	Repeat	Switch
RT (ms)	Single-block training	740 (19.95)			714 (20.07)		
	Switching-task training		843 (24.52)	892 (28.16)		780 (28.16)	819 (26.91)
ACC (%)	Single-block training	98.8 (0.29)			98.6 (0.41)		
	Switching-task training		96.9 (0.41)	96.3 (0.53)		97.7 (0.25)	97.3 (0.26)

Table 3. Mean response latencies in ms (and standard error) and mean accuracy in percentages (and standard error) for the training task.

Note: Single-block training = Single-block training group (only performed pure blocks); Switching-task training = Switching-task training group (only performed mixed blocks).

3.1 Non-linguistic task switching

Incorrect responses (3.3% of the data) and the following trial were removed as the Type of trial (repeat or switch) could not be determined after an error. In addition, response latencies shorter than 200 ms and longer than 3,000 ms together with outliers (2.5 SD from the average per participant) were discarded from the analysis. This left a total of 88.5% of the trials in the analysis.

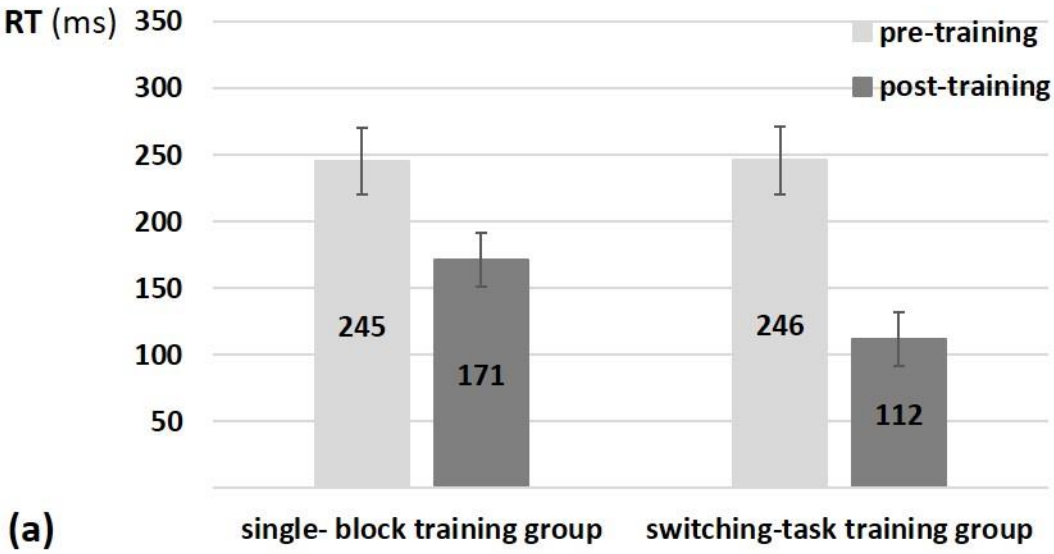
3.1.1 Switch cost. The main effect of Session was significant with faster response latencies during post-training than pre-training ($F(1,58) = 180.62$, $MSe = 28060.74$, $p < .001$, $\eta_p^2 = .757$). The main effect of Trial type was also significant with faster latencies for repeat than switch trials ($F(1,58) = 182.10$, $MSe = 12452.64$, $p < .001$, $\eta_p^2 = .758$). No main effect was found between the two training groups ($F1,58) = 1.99$, $MSe = 78535.98$, $p =.163$). These results are qualified by two- and three-way interactions: Session by Trial type ($F(1,58) = 63.95$, $MSe = 2688.19$, $p < .001$, $\eta_p^2 = .524$), and Session by Trial type by Group ($F(1,58) = 5.27$, $MSe = 2688.19$, $p = .025$, $\eta_p^2 = .083$). This analysis demonstrates the typically found switch cost and suggests that the switch cost shows group differences depending on the session. To answer our research question whether language switching training reduces non-linguistic switch cost from pre- to post-training we calculate the switch cost size (difference score of switch – repeat trials). The switch cost is used as the dependent variable with Session as within-subject factor and Group as between-subject factors.

The ANOVA revealed a main effect of Session ($F(1,58) = 63.95$, $MSe = 5376.38$, $p < .001$, $\eta_p^2 = .524$) but not of Group ($F < 1$). An interaction between Session and Group was also significant ($F(1,58) = 5.27$, $MSe = 5376.38$, $p = .025$, $\eta_p^2 = .083$). To explore the significant interaction separate analyses for the single-block training and switching-task training group. A smaller switch cost was found during post- training than pre- training for both the single-block training group ($t(29) = 3.97$, SE = 19.24, $p = .001$) and the switching-task training group ($t(29) = 7.39$, SE = 18.62, $p < .001$) demonstrating a general repetition training effect from pre- to post- training. However, the reduction of the switch cost is greater for the switching-task training (138 ms; SE = 18.62) than the single-block training group (76 ms; SE = 19.24; $t(58) = 2.29$, SE = 26.77, $p < .025$) suggesting an additional effect of mixed language switching (see Figure2a).

The accuracy data revealed a main effect of Trial type with higher accuracy for repeat than switch trials ($F(1,58) = 22.92$, $MSe = 7.87$, $p < .001$, $\eta_p^2 = .283$). There were no differences between the groups ($F(1,58) = 1.05$, $MSe = 15.41$, $p = .311$, $\eta_p^2 = .018$). None of the interactions reach significance (Trial type by Group: $F(1,58) = 1.78$, $MSe = 7.87$, $p = .187$, $\eta_p^2 = .030$; all other $Fs < 1$).

3.1.2 Mixing cost. For the response latencies the main effect of Session was significant with faster naming latencies during post- training than pre- training ($F(1,58) = 137.83$, $MSe = 10065.64$, $p < .001$, $\eta_p^2 = .704$). The main effect of Trial type was also significant with faster latencies for pure than repeat trials ($F(1,58) = 589.86$, $MSe = 14156.53$, $p < .001$, $\eta_p^2 = .910$). No main effect was found between the two training groups ($F(1,58) = 1.20$, $MSe = 28444.09$, $p = .277$, $\eta_p^2 = .020$). An interaction of Session by Trial type ($F(1,58) = 89.54$, $MSe = 4848.03$, $p < .001$, $\eta_p^2 = .607$) revealed a training effect with a smaller mixing cost during post- training (288 ms; SE = 13.75) than pre- training (458 ms; SE = 21.39; $t(59) = 9.43$, SE = 18.05, $p < .001$) (see Figure 2b). None of the other interactions reached significance (Session by Group ($F < 1$) and Trial type by Group ($F(1,58) = 2.50$, $MSe = 14156.53$, $p = .119$, $\eta_p^2 = .041$) and Session by Trial type by Group ($F(1,58) = 1.46$, $MSe = 4848.03$, $p = .231$, $\eta_p^2 = .025$)).

The accuracy data revealed a main effect Trial type was significant with higher accuracy for repeat than pure trials ($F(1,58) = 34.66$, $MSe = 3.43$, $p < .001$, $\eta_p^2 = .374$). There was an interaction between Trial type and Group ($F(1,58) = 5.13$, $MSe = 3.43$, $p = .027$, $\eta_p^2 = .081$). None of the other main effects or interactions were significant (Group: $F(1,58) = 2.22$, $MSe = 6.15$, $p = .141$, $\eta_p^2 = .037$; all other *Fs* < 1). The interaction revealed no difference between groups for pure trials ($F < 1$), but improvement on the repeat trials for the single-block training group compared to the switching-task group by 1.21% ($F(1,58) = 4.08$, $MSe = 10.88$, $p = .048$, $\eta_p^2 = .066$) which means a difference of 1 trial out of 96 trials.



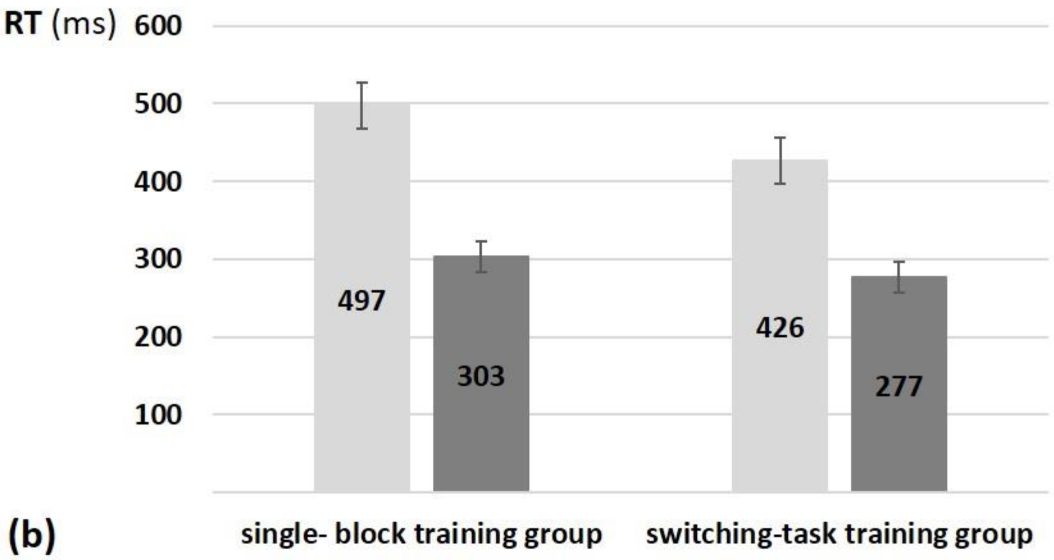


Figure 2. Difference scores for (a) the switch cost (switch – repeat) and (b) the mixing cost (repeat – pure) in the non-linguistic switching task.

3.2 Linguistic task switching

Incorrect responses were discarded (2.9% of the data), as well as the first trial after an error as the Type of trial (repeat or switch) could not be determined after an error. Further, voice-key errors were removed. In addition, naming latencies shorter than 200 ms and longer than 3,000 ms, together with outliers (2.5 SD from the average per participant) were discarded from the analysis. This left a total of 90.6% of the trials in the analysis.

3.2.1 Switch cost. For the naming latencies the main effect of Session was significant with faster naming latencies during post-training than pre-training ($F(1,58) = 12.35$, $MSe = 11209.62$, $p = .001$, $\eta_p^2 = .176$). The main effect of Trial type was also significant with faster latencies for repeat than switch trials ($F(1,58) = 152.59$, $MSe = 1693.33$, $p < .001$, $\eta_p^2 = .725$). No main effect was found between the two training groups ($F < 1$). These results are qualified by two- and three-way interactions: Session by Trial type ($F(1,58) = 10.48$, $MSe = 1078.79$, $p = .002$, $\eta_p^2 = .153$), and Session by Trial type by Group ($F(1,58) = 5.39$, $MSe = 1078.79$, $p < .024$, $\eta_p^2 = .085$). To answer our research question whether language switching training reduces non-linguistic switch cost from pre- to post-training we ran the same analysis with difference scores reflecting the switch cost.

The ANOVA revealed a main effect of Session ($F(1,58) = 10.48$, $MSe = 2157.59$, $p = .002$, $\eta_p^2 = .153$) but not of Group ($F(1,58) = 3.17$, $MSe = 3386.66$, $p = .08$, $\eta_p^2 = .052$). The interaction between Session and Group was significant ($F(1,58) = 5.39$, $MSe = 2157.59$, $p = .024$, $\eta_p^2 = .085$). To explore the significant interaction, we performed separate analyses for the single-block training - and switching-task group. The single-block training group does not reveal a training effect, reflected by no differences of the switch cost at pre-training (79 ms;

SE = 11.92) and post-training (71 ms; SE = 9.67; t $<$ 1). The switching-task training group, however, demonstrated a training effect with smaller switch cost found during post-training (33 ms; SE = 4.79) than pre-training (80 ms; SE = 10.53; t(29) = 4.01, SE = 11.79, $p < .001$) (see Figure 3a).

The accuracy data revealed a main effect of Trial type with higher accuracy for repeat than switch trials ($F(1,58) = 10.33$, $MSe = 5.24$, $p = .002$, $\eta_p^2 = .151$). There was also an interaction between Session and Group ($F(1,58) = 5.98$, $MSe = 11.42$, $p = .018$, $\eta_p^2 = .093$) and a marginal interaction between Session, Trial type, and Group ($F(1,58) = 3.59$, $MSe = 4.47$, $p = .063$, $\eta_p^2 = .058$). None of the other main effects (Session and Group: $Fs < 1$) or interactions (Session by Trial type: $F(1,58) = 1.35$, $MSe = 4.47$, $p = .250$, $\eta_p^2 = .023$; Trial type by Group: $F(1,58) = 1.68$, $MSe = 5.24$, $p = .200$, $\eta_p^2 = .028$) were significant. To explore the significant interaction we performed separate analyses for the single-block training and switching-task training group. In line with the response latencies, we saw that the single-block training group does not reveal a difference in accuracy of the switch cost between pre- (0.37%; SE = 0.42) and post-training (0.77%; SE = 0.57; t $<$ 1), but the switching-task training group does show a decrease in the switch cost from pre- (2.17%; SE = 0.66) to post-training (0.50%; SE = 0.59; t(29) = 1.99, SE = 0.83, $p = .055$).

3.2.2 Mixing cost. For the naming latencies the main effect of Trial type was significant with faster latencies for pure than repeat trials ($F(1,58) = 223.54$, $MSe = 6079.61$, $p < .001$, $\eta_p^2 = .794$). No main effect was found for Session ($F(1,58) = 2.84$, $MSe = 5657.59$, $p = .097$, $\eta_p^2 = .047$) or between the two training groups ($F < 1$). An interaction of Session by Trial type ($F(1,58) = 11.35$, $MSe = 1703.57$, $p = .001$, $\eta_p^2 = .164$) revealed a training effect with a smaller mixing cost during post-training (133 ms; SE = 12.08) than pre-training (168 ms; SE = 10.51; t(59) = 3.36, SE = 10.69, $p = .001$) (see Figure 3b). None of the other interactions reached significance (Session by Group and Trial type by Group ($F < 1$) and Session by Trial type by Group ($F(1,58) = 1.36$, $MSe = 1703.57$, $p = .248$, $\eta_p^2 = .023$).

The accuracy data only revealed a main effect of Trial type with higher accuracy for pure than repeat trials ($F(1,58) = 53.79$, $MSe = 5.24$, $p < .001$, $\eta_p^2 = .481$). None of the other main effects (Session and Group: $Fs < 1$) or interactions (Session by Group: $F(1,58) = 2.99$, $MSe = 4.38$, $p = .089$, $\eta_p^2 = .049$; Session by Trial type: $F(1,58) = 1.31$, $MSe = 2.86$, $p = .257$, $\eta_p^2 = .022$; all other $Fs < 1$) reached significance.

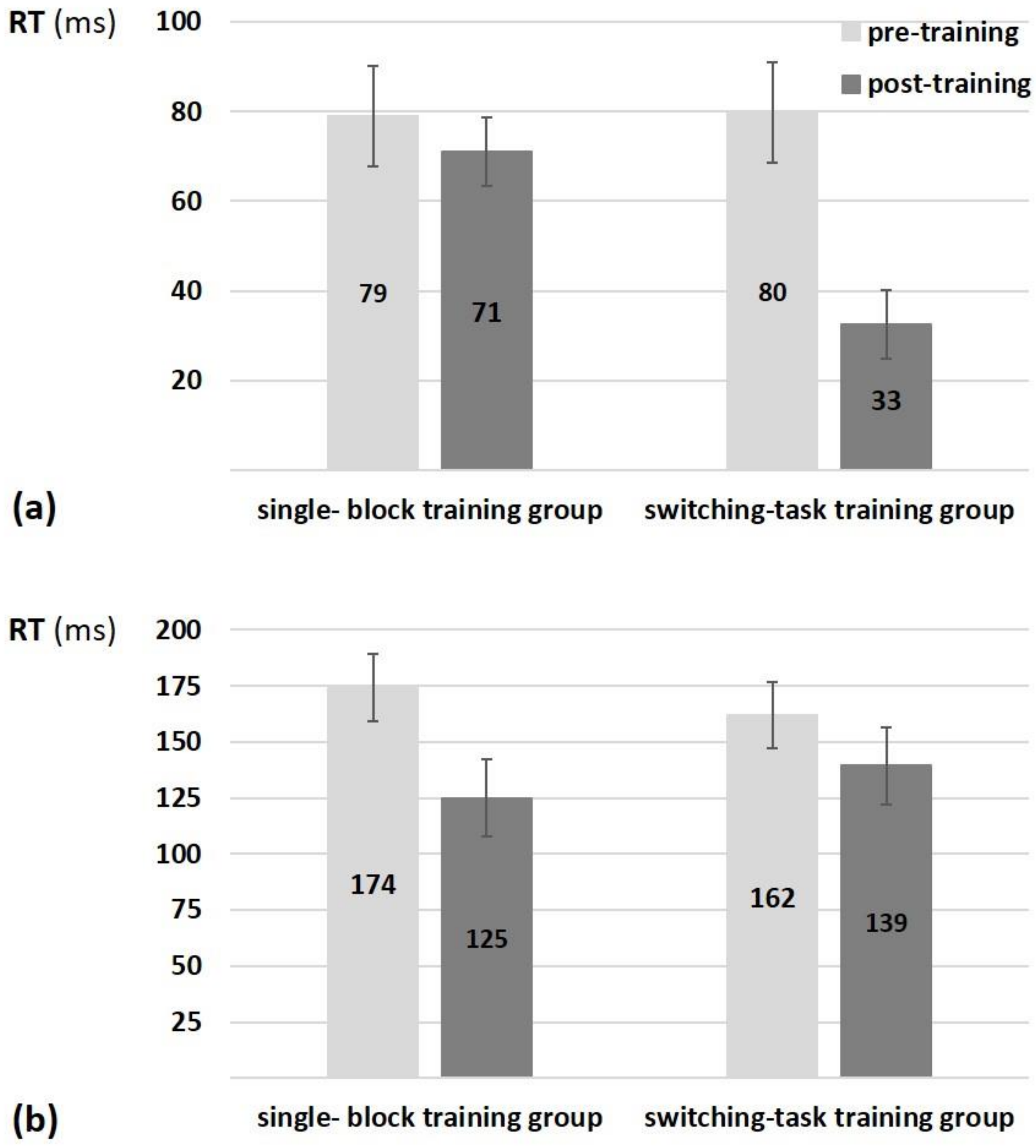


Figure 3. Difference scores for (a) the switch cost (switch – repeat) and (b) the mixing cost (repeat – pure) in the linguistic switching task.

3.3 Correlations

To investigate whether the mixing and switch costs are consistent across domains we correlated (Pearson's coefficient) each of these costs between the linguistic- and non-linguistic switching tasks. For the mixing costs, we did not find correlations across domains at pre-training (r = .198, p = .129), but at post-training there was a small correlation (r = .273, p = .035). For the switch costs, we did not find a correlation across domains, either at pre-training (r = -.004, p = .976) or at post-training (r = .172, p = .188).

3.4 Language training

For the single-block training group only pure trials were present and the effect of Session (training1 vs. training2) was analyzed. For the switching-task training group only mixed blocks were present and an ANOVA with the within-subject factor of both Session (training1 vs. training2) and Trial type (repeat vs. switch) were analyzed.

The same rules as during the linguistic experimental task were used for error (2.4% of the data) and outlier removal. This left a total of 91.0% of the trials in the analysis.

3.4.1 Single-block training group. For the naming latencies the main effect of Session was significant with faster naming latencies during the second training session than the first ($F(1,29) = 16.64$, $MSe = 616.97$, $p < .001$, $\eta_p^2 = .365$). The accuracy data showed similar performance in training session1 and 2 ($F < 1$). Mean response latencies and accuracy data for training sessions are presented in Table 3.

3.4.2 Switching-task training group. For the naming latencies the main effect of Session was significant with faster naming latencies during training2 than training1 ($F(1,29) = 29.72$, $MSe = 4707.78$, $p < .001$, $\eta_p^2 = .506$). The main effect of Trial type was also significant with faster latencies for repeat than switch trials ($F(1,29) = 69.64$, $MSe = 840.79$, p

$< .001$, $\eta_p^2 = .706$). These two factors also interacted ($F(1,29) = 5.02$, $MSe = 173.20$, $p = .033$ $\eta_p^2 = .148$). A switch cost was present at both training session 1 ($F(1,29) = 66.21$, $MSe = 556.56$, $p < .001$, $\eta_p^2 = .695$) and session 2 ($F(1,29) = 49.35$, $MSe = 457.43$, $p < .001$, $\eta_p^2 = .630$). However, this cost was smaller at the second (39 ms; SE = 5.72) than first training session (50 ms; SE = 6.09; t(29) = 2.17, SE = 4.80, $p = .038$).

The accuracy data only revealed a main effect of Session with better performance during session 2 than session 1 ($F(1,29) = 8.08$, $MSe = 0.62$, $p = .008$, $\eta_p^2 = .218$). Further, less errors were made in the repeat than switch trials ($F(1,29) = 6.51$, $MSe = 1.08$, $p = .016$, $\eta_p^2 = .183$). The interaction was not significant ($F < 1$).

4 Discussion

We studied the cross-talk between BLC and EC by testing if short-term language switching training influences EC in a non-linguistic switching task in the two groups of bilinguals. The switching-task training group was trained in language switching, involving BLC, while the single-block training group was trained in blocked naming. We reported two main results. First, while both training groups reduced the switch cost from pre- to post-training, the benefit of the training was greater for the switching-task training than the single-block training group. Second, the mixing cost was reduced equally for both groups. We show that short-term language switching training influences the switch cost, but not the mixing cost, in the non-linguistic domain. This suggests the presence of cross-talk for some sub-mechanisms of control.

The observation that language switching training reduces the switch cost in a non-linguistic switching task, to a greater degree for the switching-task training than the single-block training group, shows that training effects can be transferred from linguistic to non-linguistic tasks. In other words, for the reactive type of control (indexed by switch cost) there seems to be cross-talk between BLC and EC. This extends previous results showing transfer between different instantiations of domain-general EC (Karbach & Kray, 2009; Kray et al., 2012; Zinke et al., 2012) to cross-domain transfer effects in the present study. In contrast, the two training protocols led to the same benefit in mixing cost for both training groups. This is because the mixing cost is suggested to index a more general and global type of control (Bobb & Wodniecka, 2013; Meiran, 2010). For example, this type of control does not only include the switching process, but it also includes a more sustained type of control that keeps both languages activated over the long run. Not only did the switching-task training group have to maintain activation of both languages during language switching training, but also the single-block training group had to keep both languages activated in a sustained manner during blocked naming training. Mixing costs do not tap the language switching training specifically, but are tapped by both the switching and the blocked training. Therefore, similar benefits for the mixing cost were found for both groups. These results are in line with previous studies that suggest that the mixing cost reflects a more general type of control. For example, Cattaneo and colleagues (2015) demonstrated that the mixing cost was affected equally for the linguistic- and non-linguistic tasks by Parkinson's patients. Thus, the similar benefit on the mixing cost for both groups suggests it is not specifically BLC, but a more general proactive control.

We had also included the language-switching task during pre- and post-training with the aim to see whether these effects parallel those found in the non-linguistic task. As expected, the pattern of the linguistic results was similar to that of the non-linguistic switching task. For the switch cost, we found a reduced switch costs after training in language switching but not after training in blocked naming. This is in line with the study from Kang and colleagues (2017) who found that language switching training showed reduced language switch costs after training. This suggests that both linguistic and non-linguistic abilities can be trained with short-term language switching training.

It is important to acknowledge that repetition effects might explain that both training groups showed some decrease in the mixing and switch costs after a week, since both the design and stimuli set were the same in the pre- and post-training sessions. Within the EC literature practice with non-linguistic switching has indeed been shown to decrease both mixing and switch costs (Karbach & Kray, 2009; Prior & Gollan, 2013; Zinke et al., 2012). For the linguistic task we only found a repetition effect for both groups on the mixing cost, but not for the switch cost. This is because language switch cost has only been shown to decrease after extensive (Kang et al., 2017; Wu et al., 20178 and not after short language switching training (Prior & Gollan, 2013). Indeed, our single-block training group does not show a reduction of the switch cost between the short language switching tasks at pre- and post-training. But our switching-task training group showed a reduction of the switch cost between the two long language training sessions.

The greater reduction in switch costs after language switching compared to blocked naming training suggests that language recruits BLC processes to a stronger extent than blocked naming. Our language switching training protocol (switching-task training group) resembles the dual-language context in which bilinguals switch between their languages frequently, while our blocked language protocol (single-block training group) resembles the single-language context in which little switching occurs as each language is used in a different environment. That is, we show that, depending on the language context, bilinguals show differential usage of control mechanisms in both linguistic and non-linguistic control. This is in line with the previous literature that has suggested that the language control is flexibly adapted depending on the language context a bilingual is in (Green & Abutalebi, 2013; Timmer, Christoffels, & Costa, 2018; Timmer, Grundy, & Bialystok, 2017b). Thus, we extend these findings to show that language context not only influences language but also non-linguistic control.

Some previous studies showed that greater switching frequency in real life leads to a better performance in task-switching EC (Hartanto & Yang, 2016; Prior & Gollan, 2011; Verhagen et al., 2017; Pot et al., 2018; Verreyt et al., 2016; for a review see Yang et al., 2016; but see Jylkkä et al., 2017). This raises the question of what the relation is between our short-term language context manipulation and long-term daily language switching. Studies which investigated whether bilinguals compared to monolinguals show improved EC through reduced switch costs suggest that the origin of improved EC lies in the long-term practice in BLC bilinguals have. Those results are mixed, while some studies show reduced switch costs (Garbin et al., 2010; Houtzager, Lowie, Sprenger, & De Bot, 2017; Prior & Gollan, 2011; Prior & Macwhinney, 2010; Stasenko, Matt, & Gollan, 2017), many other studies did not (Branzi, Calabria, Gade, Fuentes, & Costa, 2018; Hernández et al., 2013; Paap et al., 2017; Paap & Greenberg, 2013; Timmer et al., 2017a). Hernández and colleagues (2013) did not reveal reduced switch costs for bilinguals but did show a reduced restart cost (cue-processing cost) for them. The restart cost is a sub-process of the switch cost that encompasses a multitude of underlying processes. This sub-process could possibly better detect the bilingual effect. Moreover, within the bilingual population it has been shown that bilinguals that have less cross-language interference have enhanced EC than bilinguals with less cross-language interference (Festman, Rodriguez-Fornells, & Münte, 2010; Prior & Gollan, 2011). The current study shows that there is cross-talk between BLC and EC in the short-term in an experimental setting, however, we need to be cautious about the relationship with long-term daily life effects. Most likely, daily language switching is not as intense as during our language switching training protocol in the experiment. What do these daily patterns of language use look like exactly for our population? Our Catalan-Spanish bilinguals used their languages respectively 70%/30% throughout the week (see Table 1). This suggests that our bilinguals frequently switched between both languages and this also makes them high-proficient, as these two factors are strongly related. It is difficult to disentangle the contribution of each of these variables to the positive effect of language training on switching abilities.

Further, at first glance our result of decreased switch costs after language switching training seem to be in conflict with a study that failed to find any effect of language switching training on non-linguistic task switching ((Prior & Gollan, 2013). The reason for this discrepancy can be found in some important methodological differences between the studies. First, our training protocol was more intense than theirs in terms of trials (1536 vs. 160). Independent research shows that extensive training leads to more robust EC training effects (Hussey & Novick, 2012; Shipstead, Redick, & Engle, 2012) and BLC training effects (Kang et al., 2017; Wu et al., 2018).[2] Second, our tasks and stimuli (non-linguistic task: more color-shape combinations; linguistic task: pictures vs. single digits) were more difficult than theirs, and this might have influenced the magnitude of the mixing and switch costs. A greater magnitude leaves more room for improvement. Third, Prior & Gollan trained on both blocked naming and language switching, while in the present study were separated and contrasted as two different trainings. Hence, a direct comparison between these studies is not completely appropriate.

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[2] An additional difference between our and their study is that we have a within-task comparison where the same group is compared from pre- to post-training. However, Prior and Gollan (2013) had a between-group comparison where they looked for improvement from pre- to post-training between two different groups which creates additional noise in the data potentially diminishing the cross-task transfer effect. Due to the within-subjects design employed here cross-task transfer cannot be examined without the possible influence of repetition effects, performing the same task at pre-training and post-training.

Another paradox with the finding of transfer for the switch cost in the present study is the fact that the correlations between linguistic- and non-linguistic switch costs are often absent. Indeed, most studies that correlated the switch cost, as a way to measure the overlap between BLC and EC, failed to find significant correlations (e.g., Branzi et al., 2016; Calabria et al., 2015, 2011; but see Declerck et al., 2017 and Timmer, Calabria, et al., 2018). We didn't find a correlation between tasks either for the switch cost and for the mixing costs the results were inconsistent. The lack of correlations could be caused by the suggestion that the switch cost reflects a multitude of underlying processes that may differ to a certain extent for the type of switching task (linguistic or non-linguistic). For example, these two types of switching tasks often use different stimuli (e.g., pictures vs. digits), and different response modalities (oral naming vs. categorization). The final performance (size of the switch and mixing cost) of an individual is affected by all sub-processes: those shared between tasks and those that have differential contributions. The strength of the correlation between tasks depends on the contribution of shared and idiosyncratic processes to people's performances. The higher the contribution of shared processes, the higher the expected correlation, and the higher the contribution of idiosyncratic processes, the lower the correlation. This has recently been exemplified by Declerck and colleagues (2017) who showed a modulation of the correlation between the tasks depending on how similar they were. Thus, the lack of correlation between linguistic and non-linguistic task might be due to the contribution of idiosyncratic processes, making it difficult to detect the contribution of possible shared processes. Another important point to consider when using cross-domain correlations for switch costs is that this correlation is that the degree of correlation is attenuated by the test-retest reliability of the measure (e.g., switch cost) in each control domain (Hedge, Powell, & Sumner, 2017; Paap & Sawi, 2016; Timmer, Calabria, et al., 2018). Specifically, the correlation between two different measures of control tasks (linguistic and non-linguistic) is always lower than the test-retest reliability of the same measure over time (intra-class correlation or Cronbach's alpha). Therefore, the lower the test-retest reliability, the less the measure distinguishes consistently between the performance of individuals within a population, the more difficult it is to detect a relationship with other constructs, as is the goal of cross-domain correlations. Thus, while cross-domain correlations did not pick up some shared processes in our study, the novel approach of training/transfer did.

But, why do we see an effect of training on the switch cost then? Possibly, with the training on a specific task, in this case language switching, specific sub-mechanisms of the switch cost are trained that underlie both instantiations of the switching task. Moreover, an ERP study in which both tasks were performed by the same participants showed that not all the sub-components related to the switch cost overlapped across the two tasks (Timmer et al., 2017a): that is, the P3 did, but the N2 component did not. This suggests that these two ERP components probably reflect different sub-processes of the switch cost with a different degree of overlap across the two tasks: while the N2 is suggested to reflect early sensory priming, the P3 is related to greater working memory required for switch trials when reconfiguring stimulus-response mappings (Periáñez & Barceló, 2009). Therefore, it could be that participants were trained on the working memory sub-component, but not attentional priming in the present study. And this training on working memory was transferred to the non-linguistic task. In line with this, Timmer and colleagues (2017a) showed that bilinguals showed more extended regional overlap of P3 activation between tasks, suggesting a possibly transfer of switch cost effects. Thus, the training task used to inspect transfer effects seems more sensitive than correlational studies.

To conclude, the present study gives new insight into the question of the underlying mechanisms of BLC and to what extent they are related to domain-general EC. We show that a sub-mechanism of the switch cost is shared to some extent across the different switching tasks. This sub-mechanism can be trained by language switching and influence a control task that does not involve any language processing. Thus, not only do bilinguals that switch a lot in their daily life show an influence on EC processing, but we also show that a specific bilingual changes the strength of usage of shared control mechanisms depending on the bilingual language context (switching between languages or confined to one language) they are in.

References

Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., … Khateb, A. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*, *18*(7), 1496–1505. https://doi.org/10.1093/cercor/bhm182

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, *20*(3), 242–275. https://doi.org/10.1016/j.jneuroling.2006.10.003

Antoniou, M., Gunasekera, G. M., & Wong, P. C. M. (2013). Foreign language training as cognitive therapy for age-related cognitive decline: A hypothesis for future research. *Neuroscience & Biobehavioral Reviews*, *37*(10), 2689–2698. https://doi.org/10.1016/j.neubiorev.2013.09.004

Bak, T. H., Long, M. R., Vega-Mendoza, M., & Sorace, A. (2016). Novelty, challenge, and practice: The impact of intensive language learning on attentional functions. *PLoS ONE*, *11*(4). https://doi.org/10.1371/journal.pone.0153485

Bobb, S. C., & Wodniecka, Z. (2013). Language switching in picture naming: What asymmetric switch costs (do not) tell us about inhibition in bilingual speech planning. *Journal of Cognitive Psychology*, *25*(5), 568–585. https://doi.org/10.1080/20445911.2013.792822

Branzi, F. M., Calabria, M., Boscarino, M. L., & Costa, A. (2016). On the overlap between bilingual language control and domain-general executive control. *Acta Psychologica*, *166*, 21–30. https://doi.org/10.1016/j.actpsy.2016.03.001

Branzi, F. M., Calabria, M., Gade, M., Fuentes, L. J., & Costa, A. (2018). On the bilingualism effect in task switching. *Bilingualism: Language and Cognition*, *21*(1), 1–14.

https://doi.org/10.1017/S136672891600119X

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural Mechanisms of Transient and Sustained Cognitive Control during Task Switching. *Neuron*, *39*(4), 713–726. https://doi.org/10.1016/S0896-6273(03)00466-5

Buchler, N. G., Hoyer, W. J., & Cerella, J. (2008). Rules and more rules: the effects of multiple tasks, extensive training, and aging on task-switching performance. *Memory & Cognition*, *36*(4), 735–748. https://doi.org/10.3758/MC.36.4.735

Calabria, M., Branzi, F. M., Marne, P., Hernández, M., & Costa, A. (2015). Age-related effects over bilingual language control and executive control. *Bilingualism: Language and Cognition*, *18*(1), 65–78. https://doi.org/10.1017/S1366728913000138

Calabria, M., Hernández, M., Branzi, F. M., & Costa, A. (2011). Qualitative Differences between Bilingual Language Control and Executive Control: Evidence from Task-Switching. *Frontiers in Psychology*, *2*, 399. https://doi.org/10.3389/fpsyg.2011.00399

Cattaneo, G., Calabria, M., Marne, P., Gironell, A., Abutalebi, J., & Costa, A. (2015). The role of executive control in bilingual language production: A study with Parkinson's disease individuals. *Neuropsychologia*, *66*. https://doi.org/10.1016/j.neuropsychologia.2014.11.006

Costa, A., Miozzo, M., & Caramazza, A. (1999). Lexical Selection in Bilinguals: Do Words in the Bilingual's Two Lexicons Compete for Selection? *Journal of Memory and Language*, *41*(3), 365–397. https://doi.org/10.1006/jmla.1999.2651

De Baene, W., Duyck, W., Brass, M., & Carreiras, M. (2015). Brain Circuit for Cognitive Control Is Shared by Task and Language Switching. *Journal of Cognitive Neuroscience*, *27*(9), 1752–1765. https://doi.org/10.1162/jocn_a_00817

Declerck, M., Grainger, J., Koch, I., & Philipp, A. M. (2017). Is language control just a form of executive control? Evidence for overlapping processes in language switching and task switching. *Journal of Memory and Language*, *95*, 138–145. https://doi.org/10.1016/j.jml.2017.03.005

Declerck, M., Koch, I., & Philipp, A. M. (2015). The minimum requirements of language control: Evidence from sequential predictability effects in language switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 377–394. https://doi.org/10.1037/xlm0000021

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

Festman, J., Rodriguez-Fornells, A., & Münte, T. F. (2010). Individual differences in control of language interference in late bilinguals are mainly related to general executive abilities. *Behavioral and Brain Functions*, *6*(1), 5. https://doi.org/10.1186/1744-9081-6-5

Garbin, G., Sanjuan, A., Forn, C., Bustamante, J. C., Rodriguez-Pujadas, A., Belloch, V., … Ávila, C. (2010). Bridging language and attention: Brain basis of the impact of bilingualism on cognitive control. *NeuroImage*, *53*(4), 1272–1278. https://doi.org/10.1016/j.neuroimage.2010.05.078

Grainger, J., Midgley, K., & Holcomb, P. J. (2010). Re-thinking the bilingual interactive-activation model from a developmental perspective (BIA-d). In *Language acquisition across linguistic and cognitive systems* (pp. 267–283). https://doi.org/10.1075/btl.128.02gar

Green, D. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, *1*(2), 67–81. https://doi.org/10.1017/S1366728998000133

Green, D., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*(5), 515–530. https://doi.org/10.1080/20445911.2013.796377

Hartanto, A., & Yang, H. (2016). Disparate bilingual experiences modulate task-switching advantages: A diffusion-model analysis of the effects of interactional context on switch costs. *Cognition*, *150*, 10–19. https://doi.org/10.1016/j.cognition.2016.01.016

Hedge, C., Powell, G., & Sumner, P. (2017, July 19). The reliability paradox: Why robust cognitive tasks do not produce reliable individual differences. *Behavior Research Methods*, pp. 1–21. https://doi.org/10.3758/s13428-017-0935-1

Hernández, M., Martin, C. D., Barceló, F., & Costa, A. (2013). Where is the bilingual advantage in task-switching? *Journal of Memory and Language*, *69*(3), 257–276. https://doi.org/10.1016/j.jml.2013.06.004

Houtzager, N., Lowie, W., Sprenger, S., & De Bot, K. (2017). A bilingual advantage in task switching? Age-related differences between German monolinguals and Dutch-Frisian bilinguals. *Bilingualism: Language and Cognition*, *20*(1), 69–79. https://doi.org/10.1017/S1366728915000498

Hussey, E. K., & Novick, J. M. (2012). The benefits of executive control training and the implications for language processing. *Frontiers in Psychology*, *3*, 158. https://doi.org/10.3389/fpsyg.2012.00158

Jost, K., Mayr, U., & Rosler, F. (2008). Is task switching nothing but cue priming? Evidence from ERPs. *Cognitive, Affective, & Behavioral Neuroscience*, *8*(1), 74–84. https://doi.org/10.3758/CABN.8.1.74

Jylkkä, J., Soveri, A., Wahlström, J., Lehtonen, M., Rodríguez-Fornells, A., & Laine, M. (2017). Relationship between language switching experience and executive functions in bilinguals: an Internet-based study. *Journal of Cognitive Psychology*, *29*(4), 404–419. https://doi.org/10.1080/20445911.2017.1282489

Kang, C., Fu, Y., Wu, J., Ma, F., Lu, C., & Guo, T. (2017). Short-term language switching training tunes the neural correlates of cognitive control in bilingual language production.

Human Brain Mapping. https://doi.org/10.1002/hbm.23765

Kang, C., Ma, F., & Guo, T. (2018). The plasticity of lexical selection mechanism in word production: ERP evidence from short-term language switching training in unbalanced Chinese–English bilinguals. *Bilingualism: Language and Cognition*, *21*(2), 296–313. https://doi.org/10.1017/S1366728917000037

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science*, *12*(6), 978–990. https://doi.org/10.1111/j.1467-7687.2009.00846.x

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: explorations of executive control processes in the task switching paradigm. *Acta Psychologica*, *101*(2–3), 339–378. https://doi.org/10.1016/S0001-6918(99)00011-6

Kray, J., Eber, J., & Karbach, J. (2008). Verbal self-instructions in task switching: a compensatory tool for action-control deficits in childhood and old age? *Developmental Science*, *11*(2), 223–236. https://doi.org/10.1111/j.1467-7687.2008.00673.x

Kray, J., Karbach, J., Haenig, S., & Freitag, C. (2012). Can Task-Switching Training Enhance Executive Control Functioning in Children with Attention Deficit/-Hyperactivity Disorder? *Frontiers in Human Neuroscience, 5*, 180. https://doi.org/10.3389/fnhum.2011.00180

La Heij, W. (2005). Selection processes in monolingual and bilingual lexical access. In J. F. Kroll & A. M. B. De Groot (Eds.), *Handbook of Bilingualism Psycholinguistic Approaches* (Vol. B (Ed). (2, pp. 289–307). Oxford, England: Oxford University Press.

Ma, F., Li, S., & Guo, T. (2016). Reactive and proactive control in bilingual word production: An investigation of influential factors. *Journal of Memory and Language*, *86*, 35–59. https://doi.org/10.1016/j.jml.2015.08.004

Meiran, N. (2010). Task switching: Mechanisms underlying rigid vs. flexible self control. In

K. N. Ochsner (Ed.), *Self control in society, mind and brain*. New York: Oxford University Press.

Minear, M., & Shah, P. (2008). Training and transfer effects in task switching. *Memory & Cognition*, *36*(8), 1470–1483. https://doi.org/10.3758/MC.336.8.1470

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology*, *66*(2), 232–258. https://doi.org/10.1016/j.cogpsych.2012.12.002

Paap, K. R., Myuz, H. A., Anders, R. T., Bockelman, M. F., Mikulinsky, R., & Sawi, O. M. (2017). No compelling evidence for a bilingual advantage in switching or that frequent language switching reduces switch cost. *Journal of Cognitive Psychology*, *29*(2), 89–112. https://doi.org/10.1080/20445911.2016.1248436

Paap, K. R., & Sawi, O. (2016). The role of test-retest reliability in measuring individual and group differences in executive functioning. *Journal of Neuroscience Methods*, *274*, 81–93. https://doi.org/10.1016/j.jneumeth.2016.10.002

Periáñez, J. A., & Barceló, F. (2009). Updating sensory versus task representations during task-switching: Insights from cognitive brain potentials in humans. *Neuropsychologia*, *47*(4), 1160–1172. https://doi.org/10.1016/j.neuropsychologia.2009.01.014

Pot, A., Keijzer, M., & de Bot, K. (2018). Intensity of Multilingual Language Use Predicts Cognitive Performance in Some Multilingual Older Adults. *Brain Sciences*, *8*(5), 92. https://doi.org/10.3390/brainsci8050092

Prior, A., & Gollan, T. H. (2011). Good Language-Switchers are Good Task-Switchers: Evidence from Spanish–English and Mandarin–English Bilinguals. *Journal of the International Neuropsychological Society*, *17*(4), 682–691. https://doi.org/10.1017/S1355617711000580

Prior, A., & Gollan, T. H. (2013). The elusive link between language control and executive control: A case of limited transfer. *Journal of Cognitive Psychology*, *25*(5), 622–645. https://doi.org/10.1080/20445911.2013.821993

Prior, A., & Macwhinney, B. (2010). A bilingual advantage in task switching. *Bilingualism: Language and Cognition*, *13*(2), 253. https://doi.org/10.1017/s1366728909990526

Rodríguez-Pujadas, A., Sanjuán, A., Ventura-Campos, N., Román, P., Martin, C., Barceló, F., … Ávila, C. (2013). Bilinguals Use Language-Control Brain Areas More Than Monolinguals to Perform Non-Linguistic Switching Tasks. *PLoS ONE*, *8*(9), e73028. https://doi.org/10.1371/journal.pone.0073028

Roelofs, A. (1998). Lemma selection without inhibition of languages in bilingual speakers. *Bilingualism: Language and Cognition*, *1*(2), 94–95. https://doi.org/10.1017/S1366728998000194

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*, *138*(4), 628–654. https://doi.org/10.1037/a0027473

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is There a Relationship between Language Switching and Executive Functions in Bilingualism? Introducing a within group Analysis Approach. *Frontiers in Psychology*, *2*, 183. https://doi.org/10.3389/fpsyg.2011.00183

Stasenko, A., Matt, G. E., & Gollan, T. H. (2017). A relative bilingual advantage in switching with preparation: Nuanced explorations of the proposed association between bilingualism and task switching. *Journal of Experimental Psychology: General*, *146*(11), 1527–1550. https://doi.org/10.1037/xge0000340

Timmer, K., Calabria, M., Branzi, F. M., Baus, C., & Costa, A. (2018). On the reliability of switching costs across time and domains. *Frontiers in Psychology*, *9*, 1032. https://doi.org/10.3389/FPSYG.2018.01032

Timmer, K., Christoffels, I. K., & Costa, A. (2018). On the flexibility of bilingual language control: The effect of language context. *Bilingualism: Language and Cognition*.

Timmer, K., Grundy, J. G., & Bialystok, E. (2017a). Earlier and more distributed neural networks for bilinguals than monolinguals during switching. *Neuropsychologia*, *106*, 245–260. https://doi.org/10.1016/j.neuropsychologia.2017.09.017

Timmer, K., Grundy, J. G., & Bialystok, E. (2017b). The influence of contextual cues on representations in the mental lexicon for bilinguals (pp. 123–142). https://doi.org/10.1075/bpa.6.06tim

Verhagen, J., Mulder, H., & Leseman, P. P. M. (2017). Effects of home language environment on inhibitory control in bilingual three-year-old children. *Bilingualism: Language and Cognition*, *20*(1), 114–127. https://doi.org/10.1017/S1366728915000590

Verreyt, N., Woumans, E., Vandelanotte, D., Szmalec, A., & Duyck, W. (2016). The influence of language-switching experience on the bilingual executive control advantage. *Bilingualism: Language and Cognition*, *19*(1), 181–190. https://doi.org/10.1017/S1366728914000352

Weissberger, G. H., Gollan, T. H., Bondi, M. W., Clark, L. R., & Wierenga, C. E. (2015). Language and task switching in the bilingual brain: Bilinguals are staying, not switching, experts. *Neuropsychologia*, *66*, 193–203. https://doi.org/10.1016/j.neuropsychologia.2014.10.037

Wu, J., Kang, C., Ma, F., Gao, X., & Guo, T. (2018). The influence of short-term language-switching training on the plasticity of the cognitive control mechanism in bilingual word production. *Quarterly Journal of Experimental Psychology*, 1-14. https://doi.org/10.1177/1747021817737520

Yang, H., Hartanto, A., & Yang, S. (2016). The complex nature of bilinguals' language usage modulates task-switching outcomes. *Frontiers in Psychology*. Frontiers Media SA. https://doi.org/10.3389/fpsyg.2016.00560

Zinke, K., Einert, M., Pfennig, L., & Kliegel, M. (2012). Plasticity of Executive Control through Task Switching Training in Adolescents. *Frontiers in Human Neuroscience*, *6*, 41. https://doi.org/10.3389/fnhum.2012.00041.

Appendix A. *Experimental stimuli language switching task.*

Catalan	Spanish	English translation
espelma	vela	'candle'
ulleres	gafas	'glasses'
ganivet	cuchillo	'knife'
got	vaso	'glass'
gàbia	jaula	'cage'
mitjó	calcetín	'sock'
taula	mesa	'table'
porc	cerdo	'pig'

Appendix B. *Stimuli used during the training phase of language switching.*

Catalan	Spanish	English translation
gos	perro	‘dog’
mussol	búho	‘owl’
papallona	mariposa	‘butterfly’
ànec	pato	‘duck’
formatge	queso	‘cheese’
raïm	uva	‘grapes’
pastanaga	zanahoria	‘carrot’
poma	manzana	‘apple’

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