Short-Term Language Switching Training Tunes the Neural Correlates of Cognitive Control in Bilingual Language Production

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Abstract: The present study investigated how language switching experience would modulate the neural correlates of cognitive control involved in bilingual language production. A group of unbalanced Chinese–English bilinguals undertook an 8-day cued picture naming training during which they named pictures in either of their languages based on visually presented cues. Participants' brain activation was scanned before and after the training in the same task. Behavioral results revealed a significant training effect such that switch costs were reduced after training. fMRI results showed that after training, activation of brain areas associated with cognitive control including the anterior cingulate cortex and the caudate was reduced. Besides, the activation reduction in the left dorsal anterior cingulate cortex positively correlated with the reduction in switch costs in response time and this training effect could be transferred to untrained stimuli. These findings suggest that neural correlates of cognitive control, especially that of the conflict monitoring process, in bilingual language production could be modulated by short-term language switching training. *Hum Brain Mapp* 38:5859–5870, 2017. © 2017 Wiley Periodicals, Inc.

Key words: bilingualism; language production; cognitive control; training; plasticity; functional magnetic resonance imaging

INTRODUCTION

Over the past decades, substantial evidence in the research on bilingualism has shown that when a bilingual produces a word in one language, the other language is activated in parallel [Colomé, 2001; Costa et al., 1999, 2000; Hoshino and

Kroll, 2008; Poarch and van Hell, 2012]. Thus, one compelling question is how bilinguals exert cognitive control to select the intended language in the face of interference from the other language [e.g., Abutalebi and Green, 2007; Green, 1998].

Previous behavior studies [e.g., Declerck et al., 2013; Gollan and Ferreira, 2009; Meuter and Allport, 1999]

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mainly adopted the language switching paradigm to examine this issue. In this paradigm, participants are required to name digits or pictures in either their first language (L1) or second language (L2) based on cues, memory or voluntarily. In a seminal study, Meuter and Allport [1999] found that performance in switch trials (the language used in the present trial differs from that used in the prior trial, such as L2-L1 and L1-L2) was worse than non-switch trials (the same language is used across two consecutive trials, such as L1-L1 and L2-L2), indicating the switch costs. Moreover, switch costs were larger when switching into the dominant L1, as compared to when switching into the weaker L2, showing an asymmetry of switch costs in unbalanced multilinguals [see also Costa and Santesteban, 2004, Exp 1; Fink and Goldrick, 2015, Exp 2; Linck et al., 2012; Ma et al., 2016, Exp 1; Philipp et al., 2007, Exp 1]. These results were interpreted as reflecting that inhibitory control is involved in bilingual language production [e.g., Green, 1998].

Studies using functional magnetic resonance imaging (fMRI) further reveal the neural basis of bilingual language control. It has been found that several cortical and subcortical brain areas related to cognitive control are recruited to ensure language selection in bilingual language production [Abutalebi and Green, 2007, 2016], including the dorsolateral prefrontal cortex [Hernandez et al., 2000, 2001; Wang et al., 2007], the inferior frontal gyrus [de Bruin et al., 2014; Luk et al., 2011], the anterior cingulate gyrus [Abutalebi et al., 2008; de Bruin et al., 2014; Guo et al., 2011; Luk et al., 2011], and the left caudate nucleus (LCN) [Abutalebi et al., 2008; Crinion et al., 2006; Luk et al., 2011; Wang et al., 2007].

Notably, it has been also proposed that such control mechanism during bilingual language production is not fixed but adapts with specific types of the bilingual experience [Green and Abutalebi, 2013]. For instance, Tu et al. [2015] found that reduced L2 exposure for one month resulted in stronger activation in the language control network during L2 sentence production. Recently, Abutalebi and Green [2016] further pointed out that some key questions that await systematic investigation are which factors of the bilingual experience induce the dynamic change, and how the brain adapts to the demands of bilingual language use. Preliminary evidence indicates that frequent language switching in daily life might modulate the language control mechanism [Christoffels et al., 2007; Garbin et al., 2011; Prior and Gollan, 2011]. In one ERP study [Kang et al., 2017], we examined the effect of language switching experience on cognitive control in bilingual language production, and found that the efficiency to establish the target language task schema could be modulated by short-term language switching training. The present study aimed to further test whether short-term language switching training would shape the neural mechanisms of cognitive control during bilingual language production.

In particular, we are interested in two specific brain areas, that is, the dorsal anterior cingulate cortex

(dACC) and the LCN. According to the previous relevant studies, these two brain regions play different roles in language control. The dACC is widely regarded as one key component of the neural network for domain-general cognitive control. Mainly responsible for task monitoring, the dACC detects a response conflict and signals the need for adjustments of cognitive control processes [e.g., Botvinick et al., 1999, 2004; Fan et al., 2003; Kerns et al., 2004; MacDonald et al., 2000]. Previous studies also revealed that the dACC is involved in cognitive control process in bilingual language production [Abutalebi et al., 2008; Guo et al., 2011], and plays a more general role in language control by monitoring the language context [Abutalebi et al., 2013].

In contrast, the LCN is mainly involved in language-specific control [Abutalebi et al., 2008; Crinion et al., 2006; Price et al., 1999]. Increased activation of the LCN has been found during language switching [Wang et al., 2007; Zou et al., 2012]. Lesions in this area severely degrade bilinguals' language switching performance [e.g., Abutalebi et al., 2009]. These findings converge on the crucial role that the LCN plays in language control. Moreover, it has been specifically associated with selecting lexical items in the target language in the face of cross-language competition [Abutalebi et al., 2008, 2013].

Based on previous findings, we hypothesized that if language switching training could modulate the neural mechanism of cognitive control in bilingual language production, activation of brain regions associated with cognitive control would differ before and after the training. To test this hypothesis, the present study recruited a group of unbalanced Chinese-English bilinguals who took part in short-term language switching training. In the pre-test session, participants completed a cued picture naming task that included two sets of well-matched pictures. One of the two picture sets was randomly assigned to be trained stimuli, leaving the other set serving as untrained stimuli. Then, all participants undertook an 8-day-long language switching training with the assigned trained stimuli. Finally, in the post-test session, they completed the same task as the pre-test. Through comparing the switching effect in brain activity related to trained stimuli in the pre-test with that in the post-test, the present study investigated how language switching training would modulate the activations of brain regions linked with cognitive control. To eliminate the potential effects of irrelevant variables (e.g., age of L2 acquisition, L2 proficiency, L2 exposure, frequency of L2 use) between subjects, the present study took the brain activation patterns of a set of untrained stimuli within the same group of subjects as control. Furthermore, as the roles of the aforementioned two brain areas in language control were different, we were interested in whether the training effect observed in the two areas, if any, could be transferred to new stimuli by comparing the training effects of dACC and LCN for the trained and untrained stimuli.

TABLE I. Attributes of pictures for set A and set B (standard deviations in parentheses)

	Familiarity		Image agreement		Visual complexity		Lexical frequency	
	Chinese norms	English norms	Chinese norms	English norms	Chinese norms	English norms	Chinese norms	English norms
Set A	4.59 (0.38)	3.55 (0.89)	3.63 (3.09)	3.56 (0.57)	2.38 (0.68)	2.84 (0.90)	116.63 (225.33)	55.23 (101.91)
Set B	4.50 (0.41)	3.40 (1.02)	3.55 (0.55)	3.72 (0.53)	2.46 (0.72)	2.97 (0.88)	104.95 (182.79)	53.38 (142.34)

Note. Chinese norms were from Zhang and Yang [2003]. English norms were from Snodgrass and Vanderwart [1980].

MATERIALS AND METHODS

Participants

The present study recruited 17 Chinese–English bilinguals (six males, age range of 18 to 25, $M = 22.1$, $SD = 2.0$). One participant dropped out. All participants were right-handed. They had normal or corrected-to-normal vision and were free of color blindness and neurological disorders. Participants received a small amount of money for their participation after the experiment.

The participants started learning English at around the age of nine. All of them had passed the College English Test Band 4 (CET-4) with an average score of 547 out of 710 ($SD = 43$). They rated their proficiency levels in both languages on a 10-point scale (1 = not fluent, 10 = very fluent). *T*-tests showed that these participants were unbalanced Chinese–English bilinguals with higher proficiency in Chinese ($M = 8.13$, $SD = 1.31$) as compared to English ($M = 5.78$, $SD = 1.42$), $t(15) = 6.990$, $P < 0.001$.

Materials

A total number of 88 black-in-white line drawings were selected from the database of Snodgrass and Vanderwart [1980]. Eight pictures were used in the practice. The remaining pictures were divided into set A and set B, each consisting of 40 pictures. Table I shows the properties of the two picture sets, including the familiarity, the image agreement, the visual complexity, and the word frequency. Paired *t*-tests showed that the aforementioned attributes of line drawings between set A and set B were comparable for both Chinese norms [Zhang and Yang, 2003] and English norms [Snodgrass and Vanderwart, 1980], $P_s > 0.269$. All pictures were easily identified with low ambiguity.

Procedure

The experiment was conducted with the approval from the Institutional Review Board of the Imaging Center for Brain Research of Beijing Normal University and complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants provided written informed consent. The present study included pre-test, training and post-test sessions. In the pre-test session,

participants first familiarized themselves with the pictures and their corresponding names in both Chinese and English outside the scanning room. Pictures were presented one by one along with their Chinese and English names. After familiarization, participants were tested on naming all pictures in Chinese and English. Those who achieved accuracy rates above 80% could start the practice. Otherwise, they had to familiarize themselves again until they could reach this threshold. The practice consisted of 16 trials. Participants were instructed to name a picture in an appropriate language according to the color of a cue. The cue was either a red or a blue frame surrounding the picture. The mapping between the color of the cue and the language was counterbalanced across participants. After the practice, participants entered the scanner to take the formal experiment.

The formal experiment adopted an event-related design. Stimuli were presented in a pseudo-randomized manner. Each trial began with a fixation cross for 300 ms, followed by a blank screen for 200 ms. Then, a picture appeared in the middle of a colored frame for 1 s. Participants were instructed to name the picture in the language indicated by the color of the frame as quickly and accurately as possible in a soft voice. A blank screen was presented for 1s, 2s, 3s, or 4s following the picture. The whole experiment included four runs. Each run contained 40 switch trials and 40 non-switch trials, each with an equal split of Chinese naming trials and English naming trials. Due to the instability of the magnetic field when the machine started to run, each run began with two filler trials, which were excluded from data analysis. Thus, each run finally contained 82 trials, lasting for 5 min and 28 s. Participants took a short break after each run. Pictures used in the first two runs were from one picture set, which was assigned as trained stimuli and would also be used for the training session. Pictures used in the last two runs were from the other set, which was assigned as untrained stimuli, and would not be used for the training session. The order of two sets of pictures was counterbalanced across participants. High-resolution anatomical images were acquired after the functional scanning. The pre-test session lasted for approximately 1 h. Due to technical limitations, verbal response data were re-collected in a behavioral lab after the scanning.

After the pre-test session, participants were asked to undergo the language switching training for 8 consecutive

days. Similar to the pre-test, participants performed a cued picture-naming task. Only trained stimuli were used in the training session. The training program included 4 blocks, each of which consisted of 41 trials. The first trial served as a filler stimulus and the remaining 40 trials consisted of 20 switch trials and 20 non-switch trials. Pictures were presented in a randomized way to avoid the order repetition effect, which might confound the training effect. The mapping between the color of the cue and the target language and the timing of the trial were identical to the pre-test session. The only difference was that in the training session, the stimuli would disappear right after participants made a response. Participants would take the training program consecutively three times for about 30 min in each day.

The post-test was performed on the day after the 8-day-long training. The procedure was identical to the pre-test.

Imaging Data Collection and Preprocessing

All of the images were acquired by a 3T Siemens Sonata whole-body MRI scanner. During the process of scanning, participants lay on the scanner table and their heads were fixed to minimize head motion. For each participant, functional scans were obtained using a single shot T2*-weighted gradient echo planar imaging sequence at 164 time points. Contiguous axial slices were procured to cover the whole brain (including cerebellum). Each functional scan had 33 slices. The following scan parameters were used: TR (repeated time) = 2,000 ms, TE (echo time) = 20 ms, flip angle = 90°, field-of-view (FOV) = 200 × 200 mm², matrix size = 64 × 64, resolution within slices = 3.1 × 3.1 mm², and slice thickness/gap = 4 mm/0.8 mm. High-resolution T1-weighted anatomical images were also acquired, using the following scan parameters: TR = 2,530 ms, TE = 3.39 ms, flip angle = 7°, FOV = 256 × 256 mm², matrix size = 256 × 256, resolution within slices = 1.3 × 1.0 mm², slice thickness = 1.33 mm, number of slices = 144. All images were scanned at intervals.

Imaging preprocessing and whole-brain analyses were performed using SPM8 (Wellcome Trust Centre for Neuroimaging, London, UK) implemented in MATLAB. The first four scans were discarded to allow magnetization to reach the equilibrium state for each participant. For the rest of the images, slice timing correction was applied to reduce differences in acquisition time between slices. The images were realigned to the first scan to correct for head motion. The realignment parameters were examined to check head motion. All participants met the inclusion criterion of showing absolute motion no greater than 2 mm. Then, the anatomical images were coregistered to the functional images for each participant. The images were then normalized to T1 template provided by SPM8 to minimize cerebral differences between participants and re-sampled with 3 × 3 × 3 mm voxels. The images were smoothed with a cubic Gaussian filter (6-mm full width at half-maximum).

Statistical Analyses

Whole brain analyses

A General Linear Model was used to estimate effects of interest for each participant. Statistical analyses were performed by modeling different conditions on a voxel-by-voxel basis. The data were globally scaled and high-pass-filtered at 128 s. Statistical analyses were performed separately for trained stimuli and untrained stimuli. Four types of effects of interest were assessed by computing the following statistical contrasts: (a) Switch trials versus Non-switch trials with trained stimuli in pre-test; (b) Switch trials versus Non-switch trials with untrained stimuli in pre-test; (c) Switch trials versus Non-switch trials with trained stimuli in post-test; (d) Switch trials versus Non-switch trials with untrained stimuli in post-test.

To examine the training effects, we compared the neural activities in the pre-test session and that in the post-test session by performing second-level analyses. Specifically, paired *t*-tests were performed to contrast the neural activation of switch costs (the contrast for Switch trials vs. Non-switch trials) in the pre-test with that in the post-test for both trained stimuli and untrained stimuli, respectively. To avoid false positive results, only clusters activated above the threshold of $P < 0.0005$ (uncorrected) were considered significant. Meanwhile, we only report significant clusters containing at least 15 contiguous voxels. Reported voxels correspond to the standardized MNI coordinate space. Besides, to examine the neural correlates associated with the switching effects, we conducted one-sample *t*-tests on the four aforementioned contrasts (for details, see Supporting Information).

ROI analyses

As indicated by previous neuroimaging studies [Abutalebi et al., 2008, 2013; Zou et al., 2012], the dACC and the LCN were important brain regions engaged in language control. Following the practice of these research [Abutalebi et al., 2008, 2013; Zou et al., 2012], the spherical ROI for the dACC was built with the averaged coordinate [−5, 6, 44] as center and 8 mm as radius. Likewise, the spherical ROI for the LCN was built with the averaged coordinate [−11, 15, 1] as center and 8 mm as radius. To investigate whether the neural activities of the dACC and the LCN significantly changed after training, we extracted the β values as the mean activation on the individual level. Then, a 2 (stimulus type: trained/untrained) × 2 (test session: pre-test/post-test) repeated-measure ANOVA was performed to examine the effect of language switching training on the neural activities in these two brain regions.

Correlation analyses

To determine the correlation between the improvements in behavior and the changes in neural activity, we performed the Pearson correlation analyses between the

Figure 1.

Switch costs (ms) as a function of training days. Error bars show one standard error.

difference in the switch costs in response time (RT) and that in the β values for the dACC and the LCN, respectively. More specifically, the β values in the correlation analyses referred to the difference in the neural activity between the switch condition and the non-switch condition for each participant.

RESULTS

Behavioral Results

RTs for correct naming trials below 300 ms and above 2,500 ms were excluded as absolute outliers, and naming latencies 2.5 standard deviations above or below each individual's mean value were then excluded as relative outliers. As participants were familiarized with picture names, their accuracy was generally high. We only performed statistical analyses on RTs.

Behavioral results during training

The mean accuracy rate of the 8-days training was 96.5%. An 8 (training days) $\times$ 2 (trial type) repeated-measures ANOVA performed on RTs showed that the main effect of training days was significant, $F(7, 105) = 3.150$, $P = 0.023$ (Greenhouse-Geisser corrected), $\eta_p^2 = 0.174$. RTs tended to decrease as training continued (869 ms, 877 ms, 860 ms, 846 ms, 844 ms, 818 ms, 835 ms, and 813 ms, respectively). The main effect of trial type was also significant, $F(1, 15) = 53.015$, $P < 0.001$, $\eta_p^2 = 0.779$, suggesting that naming switch trials (865 ms) was significantly slower than naming non-switch trials (826ms). In addition, the interaction between training days and trial type was also significant, $F(7, 105) = 6.798$, $P < 0.001$, $\eta_p^2 = 0.312$. A further paired t -test showed that there was a trend that the RT difference between switch trials and non-switch trials, the switch costs, were reduced with training (51 ms, 53 ms, 49 ms, 34 ms, 38 ms, 30 ms, 31 ms, 30 ms, respectively). This pattern is also reflected by the regression performed on switch costs over training sessions. The

regression equation was $y = -3.722x + 56.151$, $R^2 = 0.837$, $F(1, 7) = 30.759$, $P = 0.001$ (see Fig. 1).

Behavioral results of pre-test and post-test

For trained stimuli. The mean accuracy of the pre-test and the post-test for trained stimuli was 96.0%. The accuracies of switch trials in the pre-test, non-switch trials in the pre-test, switch trials in the post-test, non-switch trials in the post-test were 95.2%, 95.5%, 96.2%, 97.3%, respectively. Figure 2 presents the mean RTs of trained stimuli across different conditions. Repeated-measures 2 (test session: pre-test/post-test) $\times$ 2 (trial type: switch trial/non-switch trial) ANOVA performed on RTs showed that the main effect of test session was significant, $F(1, 15) = 27.373$, $P < 0.001$, $\eta_p^2 = 0.609$. Participants responded faster in the post-test (865 ms) than in the pre-test (1,005 ms). The main effect of trial type was also significant, $F(1, 15) = 64.101$, $P < 0.001$, $\eta_p^2 = 0.810$. Naming in switch trials (967 ms) was slower than naming in non-switch trials (903 ms). Additionally, the interaction between test session and trial type was significant, $F(1, 15) = 13.001$, $P = 0.003$, $\eta_p^2 = 0.464$. Further paired t -test showed that naming in switch trials was significantly slower than naming in non-switch trials in both the pre-test (1,047 ms and 963 ms, respectively) and the post-test (886 ms and 843 ms, respectively), $P_s < 0.001$, indicating that switch costs were reduced after training (84 ms in the pre-test and 43 ms in the post-test).

For untrained stimuli. The mean accuracy rate for untrained stimuli in the pre-test and the post-test was 93.7%. Specifically, the accuracy rates of switch trials in the pre-test, non-switch trials in the pre-test, switch trials in the post-test, non-switch trials in the post-test were 94.5%, 96.4%, 91.7%, and 92.1%, respectively. Figure 2 also shows the mean RTs of untrained stimuli across conditions. Repeated-measures 2 (test session: pre-test/post-test) $\times$ 2 (trial type: switch trial/non-switch trial) ANOVA performed on RTs showed that the main effect of test session was marginally significant, $F(1, 15) = 4.114$, $P = 0.061$, $\eta_p^2 = 0.215$. The main effect of trial type was significant,

Figure 2.

The mean RTs for switch trials and non-switch trials in pre-test and post-test for trained and untrained stimuli. Error bars show one standard error.

TABLE II. The brain regions with significantly greater activation when comparing the neural activity of the switch costs in the pre-test with that in the post-test. (uncorrected $P < 0.0005$, cluster size > 15)

Contrast	BA	Region	MNI coordinates			T value
			x	y	z	
Pre-test > post-test in trained stimuli	44	L_Inferior Frontal Gyrus	-36	36	-9	6.90
	7	L_Superior Parietal Lobule	-15	-57	57	5.47
		L_Caudate	-9	9	12	5.59
	32	R_Anterior Cingulate	15	42	6	5.79
		R_Caudate	12	9	12	5.16

$F(1, 15) = 36.14$, $P < 0.001$, $\eta_p^2 = 0.707$, indicating naming in switch trials (1,034 ms) was slower than naming in non-switch trials (960 ms). However, the interaction between test session and trial type was not significant, $F(1, 15) < 1$.

fMRI Results

Whole brain results

For trained stimuli, compared to the neural activity of switch costs (the contrast for Switch trials vs. Non-switch trials) in post-test, bilateral caudate nuclei, left inferior frontal gyrus, right ACC and left superior parietal lobule (see Table II and Fig. 3) were activated to a greater extent in the pre-test. However, no significant differences were found in any brain region when we contrasted the neural activity in the post-test with that in the pre-test. These

results suggested that the neural activation of aforementioned brain regions was reduced after language switching training for trained stimuli.

For untrained stimuli, no significant difference was found in any brain regions, when we compared the neural activity associated with switch costs in the post-test with that in the pre-test, and vice versa.

ROI results

The ROI results are shown in Figure 4. A 2 (stimulus type: trained/untrained) $\times$ 2 (test session: pre-test/post-test) repeated-measures ANOVA was performed on the β values of the dACC. The results showed that the main effect of stimulus type was not significant, $F(1, 15) = 3.270$, $P = 0.091$, $\eta_p^2 = 0.179$. The main effect of test session was significant, $F(1, 15) = 9.136$, $P = 0.009$, $\eta_p^2 = 0.379$, indicating

Figure 3.

Results of the whole brain paired t -test analysis between the neural activity of switch costs in the pre-test and post-test for trained stimuli. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 4.

(A) The spherical dACC ROI centered at $[-5, 6, 44]$ with 8-mm radius; (B) the dACC β values of the pre-test and post-test for both trained stimuli and untrained stimuli; (C) the spherical LCN ROI centered at $[-11, 15, 1]$ with 8-mm radius; (D) the LCN β values of the pre-test and post-test for both trained stimuli and untrained stimuli. [Color figure can be viewed at wileyonlinelibrary.com]

that the β values of the dACC were lower in the post-test than in the pre-test. Critically, the interaction between stimulus type and test session was not significant, $F(1, 15) < 1$.

Similarly, a 2×2 repeated-measures ANOVA was performed on the β values of the LCN. The results showed that the main effect of stimulus type was not significant, $F(1, 15) < 1$. However, the main effect of test session was significant, $F(1, 15) = 6.24$, $P = 0.025$, $\eta_p^2 = 0.294$, suggesting that the β values of the LCN were lower in the post-test than in the pre-test. In addition, the interaction between stimulus type and test session was significant, $F(1, 15) = 6.273$, $P = 0.024$, $\eta_p^2 = 0.295$. Further paired t -test showed that the β values of the LCN were lower in post-test than in pre-test for trained stimuli, $t(15) = 3.452$, $P = 0.004$. However, the β values of the LCN in pre-test did not differ from those in post-test for untrained stimuli, $t(15) < 1$.

Correlation results

The Pearson correlation analyses revealed significant positive correlation between the difference in switch costs

in RTs and that in β values of the dACC for the trained stimuli, $r = 0.723$, $P = 0.001$ (see Fig. 5A), and for the untrained stimuli, $r = 0.441$, $P = 0.044$ (see Fig. 5B). In contrast, there was no significant correlation in the LCN for the trained stimuli, $r = 0.117$, $P = 0.334$ (see Fig. 5C), or for the untrained stimuli, $r = 0.420$, $P = 0.052$ (see Fig. 5D).

DISCUSSION

The present study aimed to investigate how short-term language switching training would shape the neural mechanisms of cognitive control in bilingual language production. By training a group of unbalanced Chinese–English bilinguals with the language switching task for 8 days, the present study explored the activation patterns of brain areas underlying language control before and after the training.

Training-Induced Improvement in Behavior

The present study revealed that during the training sessions, unbalanced Chinese–English bilinguals named the

Figure 5.

The Pearson correlation between the behavioral improvements (the difference in the switch costs between the pre- and the post-test) and the neural changes (the difference in the β values of switch vs. non-switch contrast between the pre- and the post-test) in (A) dACC for trained stimuli, (B) dACC for untrained stimuli, (C) LCN for trained stimuli, (D) LCN for untrained stimuli.

pictures faster and the switch costs decreased successively. This is consistent with the finding of reduced switch costs induced by extensive practice in task-switching literature [e.g., Berryhill and Hughes, 2009; Karbach and Kray, 2009; Strobach et al., 2012], which was interpreted as suggesting the optimization of related control process [Strobach et al., 2014]. In the language switching literature, RTs of switch trials are usually longer than RTs of non-switch trials, referred to as the switch costs [Calabria et al., 2012; Christoffels et al., 2007; Costa and Santesteban, 2004; Costa et al., 2006; Declerck et al., 2015; Ma et al., 2016; Meuter and Allport, 1999; Verhoef et al., 2009]. According to the Inhibitory Control Model (IC Model) [Green, 1998], in the switch condition, the target language in the current trial was inhibited previously, thus efforts were required to relieve the inhibition, leading to the switch costs. The present study showed that the switch costs gradually reduced with training, indicating that language switching training improves unbalanced bilinguals' ability of overcoming residual inhibition from the previous trial.

We also found that after short-term language switching training, the switch costs of the trained stimuli in the post-test were smaller than that in the pre-test. This finding further indicated that participants' ability to overcome persisting inhibition was enhanced by language switching training. However, it should be noted that although the

untrained stimuli matched well with the trained stimuli, we did not observe significant training effect in behavior in the untrained stimuli. This finding is consistent with that obtained in our previous ERP studies [Kang et al., 2017], and further indicates that simple task repetition would not improve participants' behavior performance in the language switching task (to be discussed in more detail below).

Training-Induced Changes in Brain Activity

Whole brain analyses on the language switching effect showed that for the trained stimuli, left inferior frontal gyrus, right ACC, bilateral caudate nuclei, and left superior parietal lobule showed significantly reduced activity after training. No such neural activity decrease was observed in untrained stimuli. These brain areas are typical areas involved in language control [Abutalebi et al., 2008; Wang et al., 2007] and they also contribute to the general cognitive control network [Abutalebi and Green, 2007, 2008]. These results indicate that after language switching training, bilinguals could recruit less neural resources to complete the language switching task effectively, which are consistent with the behavioral results.

Further ROI analyses revealed that the activation associated with the switch effect in the dACC reduced significantly

in the post-test, as compared to the pre-test. The dACC has been reported to be more active in incongruent conditions than in congruent conditions [e.g., flanker task, Botvinick et al., 1999; a task-switching version of the Stroop task, MacDonald et al., 2000; Stroop color-naming task, Kerns et al., 2004], suggesting its crucial role in domain-general conflict monitoring. Furthermore, Abutalebi et al. [2013] associated the dACC with general task monitoring in language control. They tested trilinguals who were proficient in the L2 and less proficient in the third language (L3) in a language switching task. The results showed that switching between two languages (L1-L2, L1-L3) generated more activation in the pre-SMA/ACC than non-switching, but the degree of activation was not modulated by the proficiency differences between two languages. Besides, they also observed that within-language switching in monolinguals induced comparable activation in the pre-SMA/ACC. These results lead the researchers to conclude that dACC is responsible for the more general task monitoring, rather than language-specific control [Abutalebi et al., 2013].

Thus, the reduced activation of the dACC in the current study might indicate that bilinguals' conflict monitoring ability was improved by language switching training. The behavioral improvements correlated positively with the neural changes in this area further confirmed the enhanced ability in bilinguals to monitor language conflict in bilingual language production. Notably, there was no significant interaction between test session and stimulus type, suggesting neural reduction in both trained and untrained stimuli after training. Besides, the significant correlation between behavioral improvements and the neural changes in the dACC for both the trained stimuli and the untrained stimuli indicated that the training effect could be transferred to the untrained stimuli. This is at variance with the absence of the training effect in the untrained stimuli in behavior results. The reason for such divergence is not entirely clear, but we speculate that fMRI data may be more sensitive indices than behavioral data [e.g., Silverstein et al., 2010] to detect changes resulting from short-term language switching training, such as the adaptation of the dACC. Given that the training in the present study was relatively short (8 days with half an hour per day), it is possible that the training effect would be more robust and emerge in the behavioral data for new stimuli as well with more intensive training. Indeed, in another ERP study [Zhang et al., 2015], we observed a far transfer effect both in behavior and in ERPs from 10-day training in language switching to an attentional task.

ROI analyses on the LCN showed that after training, the activation associated with the switch effect in this region significantly decreased for the trained stimuli but not for the untrained stimuli. Additionally, for neither stimulus type did the correlation between brain activity and behavioral performance reach significance. The LCN has been considered as a crucial component of the language control network [Abutalebi and Green, 2008; Luk et al., 2011].

It has been shown to be involved in selecting the intended language in the face of cross-language interference [Abutalebi et al., 2008] and selecting the target lexical item [Abutalebi et al., 2013].

One possibility is that the activation reduction in the LCN was an after effect of activation reduction in the dACC. Our training regime might directly improve the conflict monitoring ability, reflected by the activation reduction in the dACC, which in turn improved the efficiency of the language control network, reflected by activation reduction in the LCN. This conjecture needs to be tested with further network analysis. Alternatively, the activation reduction in the LCN may reflect a practice effect due to repetitive exposure to the trained stimuli during training, which might lead to higher efficiency of lexical selection. In contrast, untrained stimuli were not presented during training, so there was no such benefit effect. It will remain for ongoing research to further test these possibilities.

Implications of the Present Findings

Notably, only training effect observed in the activation of the dACC was transferred from trained stimuli to untrained stimuli. One possibility is that short-term language switching training is more likely to modulate the general conflict monitoring process, resulting in both a training effect and a transfer effect. This speculation is consistent with the findings of two studies from our group [Kang et al., 2017; Zhang et al., 2015]. In the ERP study using a similar design, Kang et al. [2017] found that the peak latency of cue-locked N2, a negativity peaking around 200–300 ms after cue onset, was significantly shortened after 8-day language switching training. This pattern suggests that the efficiency of conflict monitoring is improved through language switching training, and this effect can be transferred to untrained materials. Critically, a number of studies have shown that the neural generator of the N2 component is located in the ACC [Bokura et al., 2001; Nieuwenhuis et al., 2003; van Veen and Carter, 2002]. Thus, the current finding of reduced activation in the dACC provides additional support for the hypothesis that language switching training improves conflict monitoring process during bilingual word production. Language switching training might lead to more rapid conflict monitoring, which in turn resulted in less activation in the dACC.

In another study, Zhang et al. [2015] observed a far transfer effect of 10-day language switching training in the AX-Continuous Performance Task, which examines domain-general executive control. Specifically, except for the behavioral improvement, an enhanced N2 for processing probe stimuli was found after training, indicating that language switching training improves the proactive aspect of domain-general executive control in unbalanced bilinguals. These findings together implicate that language

switching experience might improve general cognitive control ability, especially the conflict monitoring process, and that it is more likely to observe improvement in behavior with a longer training period.

This also provide a hint for the possible factors for the bilingual advantage in cognitive control [Bialystok et al., 2004]. A number of studies reported that bilinguals outperformed their monolingual counterparts in various executive control tasks (e.g., Simon, Stroop, Flanker, and task-switching tasks) across different stages of life, including childhood [Carlson and Meltzoff, 2008], young adulthood [Bialystok et al., 2008; Costa et al., 2008], and later adulthood [Bialystok et al., 2004, 2008]. Abutalebi et al. [2012] also documented that bilinguals recruit less neural resources in brain areas related to executive control when they completed the flanker task. Although the bilingualism has been associated with advantage in executive control, it remains unclear which aspects of the bilingual experience induce the advantage. Recent studies suggest that a range of factors are likely to contribute to this benefit, including language switching frequency [Prior and Gollan, 2011; Verreyt et al., 2016] and second language use frequency [Pliatsikas et al., 2015]. From this perspective, the findings of the present study imply that the language switching experience may potentially contribute to the bilingual advantage.

CONCLUSION

In conclusion, the present study revealed that the activation of the dACC and the left caudate was significantly reduced by short-term language switching training, and that the activation reduction of the ACC was positively correlated with the reduction in switch costs in RTs. These findings indicate that language switching training could improve the conflict monitoring ability of unbalanced bilinguals. In other words, after training, bilinguals could more efficiently monitor conflict and select the lexical item in target language by recruiting less neural resources. Our results further imply that language switching experience might be one potential contributors to the bilingual advantage in executive control. It is worth noting that there are a variety of language switching types in daily life, of which the underlying cognitive control processes might be different from each other [Green and Abutalebi, 2013]. Thus, different language switching experience might trigger different adaptation of language control mechanism and in turn lead to different features of bilingual advantages in cognitive control, which calls for more studies to further investigate [see also, Verreyt et al., 2016].

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