Language switching training modulates the neural network of non-linguistic cognitive control

Mo Chen¹, Fengyang Ma², Zhaoqi Zhang¹, Shuhua Li¹, Man Zhang¹, Qiming Yuan¹, Junjie Wu³, Chunming Lu¹,4, Taomei Guo¹,4*

¹ State Key Laboratory of Cognitive Neuroscience and Learning & IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, P. R. China, ² School of Education, University of Cincinnati, Cincinnati, Ohio, United States of America, ³ Key Research Base of Humanities and Social Sciences of the Ministry of Education, Academy of Psychology and Behavior, Tianjin Normal University, Tianjin, China, 4 Center for Collaboration and Innovation in Brain and Learning Sciences, Beijing Normal University, Beijing, P. R. China

* guotm@bnu.edu.cn

Abstract

Bilingual language experience, such as switching between languages, has been shown to shape both cognitive and neural mechanisms of non-linguistic cognitive control. However, the neural adaptations induced by language switching remain unclear. Using fMRI, the current study examined the impact of short-term language switching training on the neural network of domain-general cognitive control for unbalanced Chinese-English bilinguals. Effective connectivity maps were constructed by using the extended unified structural equation models (euSEM) within 10 common brain regions involved in both language control and domain-general cognitive control. Results showed that, the dorsal anterior cingulate cortex/pre-supplementary motor area (dACC/pre-SMA) lost connection from the right thalamus after training, suggesting that less neural connectivity was required to complete the same domain-general cognitive control task. These findings not only provide direct evidence for the modulation of language switching training on the neural interaction of domain-general cognitive control, but also have important implications for revealing the potential neurocognitive adaptation effects of specific bilingual language experiences.

Introduction

With economic globalization, an increasing number of people use two or more languages in their daily lives. These individuals are termed bilinguals or multilinguals. Different from monolinguals who can speak only one language, bilinguals need to switch between languages. In the bilingual literature, it has been hypothesized that in these processes, executive control is recruited to coordinate their two languages [1]. Therefore, long-term bilingual experience could potentially modulate domain-general executive control functions to a certain degree [2].
In the current study, we aim to investigate how language switching, one important aspect of bilingual experiences, impacts the cognitive control neural networks.

In the investigation of bilingualism, one fundamental and hotly debated issue is to determine its consequences on the brain and mind [3, 4]. For example, many studies have examined the influence of bilingual experience on bilingual executive control, but reported mixed evidence. One line of research has compared bilinguals with their monolingual peers, reporting that when completing non-linguistic executive function tasks, particularly tasks engaging conflict control functions, e.g., the Simon Task, the Flanker Task, and the Stroop Task, bilinguals exhibit a smaller conflict effect (i.e., the difference between inconsistent and consistent conditions), suggesting cognitive accommodations to bilingual experience in cognitive control [2, 5, 6]. Furthermore, a number of functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) studies have explored how bilingual language experience modulates brain plasticity by comparing bilinguals and monolinguals in the neural mechanisms of executive control [7–12]. So far, brain imaging evidence available has shown that activation patterns in a number of brain regions differ between bilinguals and monolinguals when they perform cognitive control tasks [7, 8, 11, 13, 14]. Since these brain areas play crucial roles in both cognitive control and language control [7, 10, 15], these findings suggest that bilingualism leads to neurological changes in control mechanisms. In contrast, some studies did not reveal any difference between bilinguals and monolinguals in certain executive control tasks in behavioral data [4, 16, 17].

Considering the incongruent results reported, it has been noted that bilingualism is not a monolithic construct [12, 18]. Rather, bilingualism is a multifaceted and complex phenomenon, which involves variations in a myriad of factors, such as age, age of acquiring the second language, language proficiency, language context, language experience, language use, linguistic distance [9, 19–22]. Therefore, viewing bilingualism as an all-or-none phenomenon and adopting the binary design of comparing bilinguals with monolinguals may have obscured the potential cognitive effects of heterogeneous characteristics in various bilingual sub-populations, leading to mixed evidence [21, 23].

Indeed, a new trend in examining the bilingual cognitive control focuses on testing whether various bilingual experiences modulate bilingual cognitive control in order to identify the sources that may lead to bilingual effects on cognition and brain plasticity [19–21, 23–27]. For example, DeLuca et al. [25] found that the L2 immersion were related to different patterns of structural plasticity in brain regions associated with cognitive control, such as the right caudate, right putamen, bilateral thalamus. Critically, among a range of variables related to bilingual language use, language switching is a unique language experience that bilingualism offers. It is widely believed that language control is required in proficient bilinguals when switching between two languages frequently in daily life, particularly during language production in contexts where bilinguals choose the target language based on specific interlocutors (i.e., the dual-language context proposed in the Adaptive Control Hypothesis [28]). This particular language use experience could be one of the influential factors of the change in cognitive control mechanisms as a result of the bilingual experience. One reliable window to examine the modulation of bilingual experience on cognitive control mechanisms and brain plasticity is to investigate how training in language processing affects cognitive control [27, 29, 30].

Currently, only a few studies have investigated how language switching training impacts domain-general executive control. Firstly, in one of our previous studies, Zhang et al. [31] trained Chinese-English bilinguals in a language switching task and tested them with an AX version of the Continuous Performance Test (AX-CPT). In this task, letters A and B were cues followed by letters X or Y as probes, and participants were asked to press the YES key only when they saw the AX combination. Results showed that the N2 component, a negative-going
component peaking at around 200 ms after stimulus onset, was enlarged at the cue phase after training in the training group, but not in the untrained control group. These findings suggest that language switching training enhances bilinguals’ proactive control abilities, i.e., modulating the activation levels of stimuli prior to their activation [32], specifically strengthening attention control for cue detection. In addition, Timmer, Calabria, and Costa [33] found that two sessions of language switching training led to a larger reduction in switching costs (differences between switch trials and non-switch trials) in a non-linguistic color-shape judgment task, as compared to blocked picture naming training. These results also indicate that language switching training can improve non-linguistic cognitive control. To the best of our knowledge, no previous studies have examined the functional connectivity variations underlying the language switching training effects on domain-general executive control. This type of evidence will further reveal the neuroplasticity of bilinguals induced by the factor of language switching.

In the current study, we aim to further examine how language switching training shapes the neural correlates of cognitive control mechanisms in bilinguals. We are interested in the connections among the critical brain regions involved in both language control and cognitive control. We randomly assigned 46 Chinese-English bilinguals into an experimental group and a control group. At the pre- and post-test sessions, both groups performed a task switching task. During the training phase, the experimental group received language switching training for eight consecutive days. As revealed in our previous study [34], the brain network of language control and domain-general cognitive control involves at least 10 crucial regions, including the bilateral middle frontal gyrus, the dorsal anterior cingulate cortex/ pre-supplementary motor area (dACC/pre-SMA), the left inferior parietal lobule, the bilateral anterior insula/ inferior frontal gyrus (AI/IFG), the left caudate, the bilateral thalamus, and the cerebellum. By analyzing the connectivity patterns among those regions of interest (ROIs) using the extended unified structural equation models (euSEM), we aimed to examine the influence of language switching training on the neural network of cognitive control from the connectivity perspective. Based on previous findings that language switching training can facilitate domain-general cognitive control [33] and that daily language switching experience affects functional connectivity [19, 21, 35, 36], we predicted that language switching training would change the pattern of effective connection of cognitive control network. This attempt will contribute to our understanding of the neurocognitive adaptation to the specific language experience of language switching and provide insights for the current debate on whether bilingualism causes adaptations in the brain.

Materials and methods

Participants

Forty-six Chinese-English bilinguals (28 females, M = 22.7 years, SD = 2.1 years) were randomly assigned to experimental and control groups. All were right-handed healthy young adults with normal or corrected to normal vision. None reported a history of neurological or psychiatric diseases. Data from three participants were excluded from further analyses because of excessive head movement (i.e., > 3 mm), data from two participants were excluded due to low accuracy (i.e., < 70%). Also, one participant dropped out of the study after the pre-test session. Therefore, the final sample consisted of 20 participants in each group. They were well matched on age, gender, second language (L2) proficiency measured by the College English Test Band 4 (CET-4), L2 age of acquisition (AOA), and fluid intelligence (see Table 1). CET scores were normalized by average (i.e., 500) and standard deviation (i.e., 70). The full score is 750. For self-rating scores of language proficiency, the between-subject factor Group (experimental group vs. control group) and within-subject factor Language (first language (L1) vs. L2) were analyzed. The results revealed that the experimental group showed a significant improvement in both L1 and L2 proficiency compared to the control group. These findings suggest that language switching training can enhance language proficiency in both L1 and L2.

Discussion

The current study provides evidence for the neuroplasticity of bilinguals induced by the factor of language switching. The findings suggest that language switching training can improve non-linguistic cognitive control and shape the neural correlates of cognitive control mechanisms in bilinguals. These results contribute to our understanding of the neurocognitive adaptation to the specific language experience of language switching and provide insights for the current debate on whether bilingualism causes adaptations in the brain. Further research is needed to explore the underlying mechanisms and long-term effects of language switching training on cognitive control and language proficiency.
L2) were examined in a 2-way ANOVA. The self-rating score of L1 proficiency (M = 8, SD = 1.4) was significantly higher than that of L2 proficiency (M = 5.5, SD = 1.3), \( F(1, 38) = 124.62, p < 0.001, \eta^2_p = 0.766 \). The main effect of group was not significant, \( F(1, 38) = 2.68, p = 0.11, \eta^2_p = 0.066 \). The interaction between language and group was not significant, \( F < 1 \).

These patterns suggested that participants in both groups were unbalanced bilinguals with a dominant L1. The self-reporting language switching questionnaire was used to measure language switching experience in their daily life on a 5-point scale [37], which quantified the frequency of language switching: never (1), rarely (2), occasionally (3), frequently (4), or always (5). Average level of contextual switching (e.g., There are situations in which I always switch between two languages) for both groups were 1.6 and 1.45, respectively. There was no significant difference between two groups, \( t(38) = 0.536, p = 0.595 \).

**Procedure**

The study was approved by the Ethical Committee of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University. Informed written consent was obtained from all participants. As shown in Fig 1, all participants completed identical pre and post-tests with an interval of 8 days. The experimental group received an 8-day training session between the two test sessions, while the control group did not receive any training.

**Pre- and post-test sessions**

The task switching task. In the MRI scanner, all participants completed the task switching task. The stimuli were red and blue arrows, either pointing to the right or the left. Participants followed different rules to make a response according to the color of the arrow presented (red or blue). When the arrow was in one color (e.g., red), they were asked to press the key on the same side to which the arrow pointed (e.g., press the key on the left when the arrow pointed to the left). When the arrow was in the other color (e.g., blue), they were supposed to press the key on the opposite side to which the arrow pointed (i.e., press the key on the right when the arrow pointed to the left). On switch trials, the colors of arrows in two consecutive trials were different. In contrast, on non-switch trials, the arrows in two consecutive trials were of the same color. Each trial began with a fixation cross presented for 200 ms, followed by a blank screen of 300 ms. Then, a red or blue arrow, pointing either to the left or to the right, was presented in the center of the screen for 1000 ms. The participants were asked to press the appropriate key with either their left or right thumb as accurately and quickly as possible. The arrow was then replaced by a blank screen jittered randomly for 1, 2, 3, or 4 seconds before the next trial started (i.e., the inter-stimuli intervals). The color-rule assignment was counterbalanced across participants. Half of the trials were switch trials. Participants’ response times and accuracies were automatically collected by the E-Prime 2 software (Psychology Software Tools, Pittsburgh, PA).
Both the pre-test and post-test contained 2 runs, each of which consisted of 82 stimuli and lasted for 5 minutes 28 seconds. On the first day, participants received structural scan after functional scan. Then they completed Raven Standard Progressive Matrices outside MRI scanner. On the last day, all participants filled out the Language History Questionnaire after scanning.

**Training sessions**

**The language switching training task.** Participants in the experimental group received language switch training for eight consecutive days. A total number of 48 black-and-white line-drawings were selected from the Snodgrass and Vanderwart database [38]. Eight of them were used as practice trials, and the rest of the pictures were used in the formal experiment. A blue or red frame serving as the language cue was presented simultaneously with a picture inside it. Participants were asked to name the picture in either Chinese or English indicated by the color of the frame as quickly and accurately as possible. A trial began with a blank screen of 300 ms, followed by a fixation cross of 200 ms. Then, a picture with a color frame was presented for a maximum duration of 1 second and disappeared upon a detected naming response. Finally, a blank screen was presented for 1 or 2 seconds before the next trial. Two
languages were used to name two successive pictures on switch trials, whereas the same language was used to name two consecutive pictures on non-switch trials. The cue-language mapping was counterbalanced across participants. Participants were trained on the same color-language association during training sessions. Lasting approximately 30 minutes, training on each day included three sessions with four blocks in each session. Each block consisted of 41 trials. On each training day, 40 pictures were presented randomly, and every picture was repeated 6 times for switch and non-switch conditions. Participants’ response times were recorded by an E-prime Serial Response Box (Psychology Software Tools, Pittsburgh, PA) with a plugged-in microphone, while their naming responses were recorded by a digital recorder and transcribed by experimenters to collect naming accuracies.

fMRI data acquisition
Pre- and post-test sessions were conducted in the 3T Siemens Sonata MRI (Magnetic Resonance Imaging) scanner (Trio Systems, 12-channel sense head coil, TR = 2,000 ms, TE = 20 ms, FOV = 200×200, matrix size = 64×64, 33 axial slices per volume, 164 volumes per each run, in-plane resolution = 3.1mm×3.1mm, slice thickness/gap = 4 mm/0.8 mm). Thirty-three axial slices were collected with an interleaved acquisition order. Each run was preceded by 4 dummy scans that were discarded prior to analyses. After the functional MRI scan, a high-resolution structural MRI scan was acquired for each participant (144-slice T1-weighted image, TR = 2530 ms, TE = 3.93 msec; flip angle = 7˚, slice thickness = 1.33mm, resolution within slices = 1.0 × 1.0 mm²).

fMRI image preprocessing
fMRI pre-processing was performed with DPABI [39]. The first 4 volumes from each subject were discarded to allow for magnetization equilibrium. The remaining 160 volumes were corrected for time delay between different slices by resampling with the middle (thirty-third) slice in time as a reference point and realigned to the first volume to estimate the head motion parameters. Data from three participants were excluded due to rotation larger than 3.0 or displacement larger than 3 mm. Next, T1-weighted anatomical images were co-registered to functional images followed by normalization by using EPI templates at a re-sliced voxel size of 3×3×3 mm³. Finally, the images were smoothed using a Gaussian kernel with 6×6×6 mm³ full-width at half maximum (FWHM).

Effective connectivity analysis
Firstly, based on our previous study [34], effective connectivity analyses among 10 ROIs was conducted by using extended unified structural equation models (euSEM) via the GIMME program [40]. GIMME generates individual maps and a group map based on connections shared by the majority of individuals (i.e., more than 75%). Criterion setting was based on the probability of detecting whether a true connection should exist in a given sample by sets of simulated data [41] and was used in previous empirical data [42–44]. Two criteria were met in the final model: confirmatory fit index (CFI) values > 0.90, nonnormed fit index (NNFI) values > 0.90. At the post-test session, data from one participant in the control group were removed due to the lack of convergence of the model. Specifically, this participant’s fit index was beyond 3 standard deviation of the group average fit index. Therefore, 20 participants in the experimental group and 19 participants in the control group were entered in the further analyses separately for pre- and post-test sessions.

Furthermore, the nodes of network for each group at the pre-test session were divided into core and periphery regions to detect hubs based on an optimal core-periphery subdivision
algorithm [45]. The core-ness (Q) was computed to quantify the goodness of the optimal core-periphery subdivision, with positive values indicating a possible presence of core-periphery structure [46], using brain connectivity toolbox (http://www.brain-connectivity-toolbox.net). The core brain regions were densely connected, while peripheral ones were sparsely connected.

In addition, degree means the number of neighbors a node has, reflecting importance of nodes in the network. In the directed network, a node is important if there are many other nodes that link to it ($k^{in}$), or if it links to many other nodes ($k^{out}$). In social networks, in-degree (i.e., a person with many followers) is more important than out-degree (i.e., someone who follows many other people) (Fornito et al., 2016). In brain networks, in-degree and out-degree are also informative. That is, out-degree represents what influence the central nodes exert on other nodes, and in-degree allows us to identify putative sinks of information that receive a large amount of afferent information [47]. As for detected hubs, we calculated the in-degree $k^{in}_i$, i.e., the number of edges pointed from other nodes to $i$th node, and out-degree $k^{out}_i$, i.e., the number of edges pointed from $i$th node to other nodes, from individual connectivity maps for each group at both test sessions.

Subsequently, to examine the language training effect on the cognitive control network, permutation tests were performed to examine whether the nodal degree showed significant changes between pre- to post-test sessions in both groups. More precisely, half observations were drawn without replacement from original dataset and assigned to one set, all remaining observations were assigned to another set. We could compute difference between two sets of observations by one permutation. Through 1000 permutations, null distribution of random difference was obtained. Then, $p$ values of true difference between pre-test and post-test could be calculated according to null distribution. If a $p$ value was smaller than significance threshold (i.e., $p \leq 0.05$), null hypothesis (i.e., there is no significant difference across test sessions) would be rejected.

Behavioral results

Training sessions. For the experimental group, we examined language switching costs, i.e., difference between switch trials and nonswitch trials over 8 training sessions to see if language switching training would induce any improvement of language control as shown in our previous study [48]. First, reaction times for correct trials below 200 ms or above 1500 ms were excluded from analyses as outliers (absolute outliers: 0.9%). Secondly, we rejected reaction times more than 2.5 standard deviations from the mean of each individual (relative outliers: 2.3%).

Linear regression analysis was then conducted on switch costs across 8 training days. As shown in Fig 2, there was a significant decrease in switch costs with training (regression model: $y = -2.135x + 46.703$, $F(1,155) = 4.68$, $p = 0.032$, $r^2 = 0.029$).

Pre-test and post-test sessions

Same trimming process was used for data at the pre- and post-test sessions (absolute outliers: 0.2% at the pre-test and 0.5% at the post-test for the experimental group and 0.1% at the pre-test and 0.6% at the post-test in the control group; relative outliers: 2.4% at the pre-test and 2.4% at the post-test for the experimental group and 2.1% at the pre-test and 2.4% at the post-test in the control group). All behavioral results are shown in Table 2.

For reaction times, a between-subject factor Group (experimental group vs. control group) two, and two within-subject factor Trials Type (switch vs. non-switch) and within-subject factor Test Session (pre-test vs. post-test) were examined in a 3-way ANOVA. Results showed
that the main effect of trial type was significant, $F(1, 38) = 51.09, p < 0.001, \eta^2_p = 0.573$, suggesting that participants were significantly slower in switch trials (573 ms) than non-switch trials (547 ms). However, the main effect of test session, $F(1, 38) = 1.86, p = 0.18, \eta^2_p = 0.047$, and the main effect of group, $F < 1$, were not significant. Neither the two-way interactions nor the three-way interaction was significant, $F_s < 1$.

The same ANOVA analysis was conducted for accuracy data. Results showed that the main effect of trial type was significant, $F(1, 38) = 8.01, p = 0.007, \eta^2_p = 0.174$. However, the main effect of test session, $F(1, 38) = 3.57, p = 0.066, \eta^2_p = 0.086$, and the main effect of group, $F < 1$, were not significant. Neither the two-way interactions (test session by group: $F_s < 1$; trial type by group: $F(1, 38) = 1.33, p = 0.256, \eta^2_p = 0.034$; test session by trial type: $F(1, 38)s < 1$) nor the three-way interaction was significant, $F < 1$.

### Results for effective connectivity analyses

euSEM analyses were conducted for the data of both groups at the pre- and post-test sessions, respectively. The maps had excellent fits to the data for all participants, in experimental group (pre-test: CFI = 0.9860 ± 0.0050, NNFI = 0.9645 ± 0.0128; post-test: CFI = 0.9875 ± 0.0044,

| Reaction time | Pre-test | Post-test |
|---------------|----------|-----------|
|               | Switch   | Non-switch| Switch   | Non-switch |
| Experimental group | 558 (114) | 534 (117) | 574 (95) | 551 (93) |
| Control group   | 587 (79)  | 561 (84)  | 594 (80) | 568 (90) |
| Accuracy        | 95% (7%)  | 97% (4%)  | 95% (6%) | 96% (6%) |
| Experimental group | 97% (4%)  | 98% (2%)  | 95% (5%) | 96% (6%) |

Table 2. Behavioral performance in the task switching task. Means of reaction times and accuracy (standard deviations in parentheses) for the experimental and control groups at the pre- and post-test sessions.
NNFI = 0.9645 ± 0.0094) and control group (pre-test: CFI = 0.9850 ± 0.0051, NNFI = 0.9615 ± 0.0109; post-test: CFI = 0.9840 ± 0.0060, NNFI = 0.9605 ± 0.0136).

Brain networks were visualized using the BrainNet Viewer [49]. As shown in Fig 3, the dACC/pre-SMA exerted influence on the bilateral middle frontal gyri within the frontal area in both groups at the pre-test session. In addition, the left middle frontal gyrus linked with the...
right middle frontal gyrus. Besides, information flowed from the dACC/pre-SMA to the left inferior parietal lobule in the control group. Within the subcortical area, both groups showed similar connections from the left caudate to the right thalamus, then to the left thalamus. Additionally, the left insula exerted an influence on the left caudate for the control group. Regarding links between cortical and subcortical areas, dACC/pre-SMA showed feedback loop between the bilateral AI/IFG and received signals from the right thalamus in both groups. The dACC/pre-SMA also connected with the left caudate for the experimental group. Another shared direct connection for both groups was from the right thalamus to cerebellum.

Despite the slight differences based on visual inspection, the hubs of network were shared for both groups, i.e., the dACC/pre-SMA and the right thalamus at the pre-test session (Q = 0.81 for the experimental group; Q = 0.73 for the control group). Subsequently, we examined whether the degrees of hubs exhibited differences between two groups at the pre-test session, and whether degrees of hubs showed different change patterns between both groups from pre-test to post-test session.

At the pre-test, there wasn’t significant different in $k_{\text{in}}$ for experimental and control group ($\Delta k_{\text{in}}^{\text{dACC/pre-SMA}} = -0.3$, $p = 0.97$; $\Delta k_{\text{in}}^{\text{right thalamus}} = 0.1$, $p = 0.17$). However, $k_{\text{out}}$ in the experimental group is larger than that in the control group ($\Delta k_{\text{out}}^{\text{dACC/pre-SMA}} = 0.7$, $p < 0.001$; $\Delta k_{\text{out}}^{\text{right thalamus}} = 0.5$, $p = 0.004$) at the pre-test session. Thus, we only examined whether the in-degree of hubs would be modulated by training. For the experimental group, $k_{\text{in}}^{\text{dACC/pre-SMA}}$ at the pre-test session than was larger than that at the post-test ($\Delta k_{\text{in}}^{\text{dACC/pre-SMA}} = 0.7$, $p < 0.001$). In contrast, there was no significant increase in $k_{\text{in}}^{\text{right thalamus}}$ across test sessions for the experimental group ($\Delta k_{\text{in}}^{\text{right thalamus}} = -0.1$, $p = 0.617$). For the control group, there was no significant difference in $k_{\text{in}}$ within the dACC/pre-SMA and the right thalamus across test sessions for control group ($\Delta k_{\text{dACC/pre-SMA}} = -0.7$, $p = 0.99$; $\Delta k_{\text{right thalamus}} = -1.0$, $p = 0.99$).

**Discussion**

The current study investigated the impact of short-term language switch training on domain-general cognitive control in bilinguals by characterizing the associated changes in functional network connectivity.

First of all, we observed similar connectivity patterns among 10 ROIs crucial to cognitive control in both the experimental and control groups at the pre-test session. Specifically, the dACC/pre-SMA and the right thalamus were identified as hubs within the neural network of domain-general cognitive control for both groups. These two hubs are key components of the cingulo-opercular (CO) network supporting sustained attentional control \[50, 51\]. Specifically, they transmit information with peripheral nodes to integrate multiple signals both within the CO network and across networks \[50\]. The dACC is linked to a diversity of cognitive functions, including detecting conflicts, monitoring performance, and exerting control selection \[7, 51–53\]. Shenhav et al. \[54\] showed that the dACC evaluated the expected value of control to a given trial and allocated control resources to optimize behavior based on random switching rules. Also, noninvasive brain-stimulation studies using transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) techniques have confirmed the causal role of the pre-SMA in inhibitory control \[55–59\]. For example, Yu and colleagues \[59\] found that after stimulating pre-SMA using tDCS, participants’ stopping efficiency was enhanced, together with stronger activation in the pre-SMA and increased functional connectivity between the pre-SMA and the ventral medial prefrontal cortex. These results suggest that the interplay between pre-SMA and prefrontal cortex is crucial for cognitive control.
The other hub, the right thalamus has also been shown to be engaged in executive control in various executive tasks, such as the go/no-go task and the N-back task [60]. In our recent study, Wu et al. [34] determined the dACC/pre-SMA as a hub of cortical regions and the right thalamus as a hub of subcortical regions for domain-general cognitive control. In the present study, we again revealed that the dACC/pre-SMA integrated with the bilateral middle frontal gyrus and anterior insula/inferior frontal gyrus, and that the right thalamus served as a hub connecting with the left caudate and the left thalamus during domain-general task switching. Consistent with previous studies, our findings provide additional evidence for the significant roles of the dACC/pre-SMA and the thalamus in domain-general cognitive control.

More importantly, the present study revealed that language switching training significantly reduced the incoming link of the dACC/pre-SMA in the neural network for cognitive control. Specifically, for the experimental group, the dACC/pre-SMA lost connection from the right thalamus during domain-general task switching at the group level after training. In contrast, the control group did not show any significant difference in the hubs’ degrees between pre- and post-test sessions. This connection has been shown to play important roles in both language control and cognitive control [34] and in multiple cognitive tasks [61]. Also, the connection between the posterior ACC and the thalamus has been related to response selection [62].

In the current study, response selection was crucial during both language switching and task switching tasks, as participants needed to select responses for each trial based on randomly presented cues. Critically, previous studies associated lower connectivity with less cognitive costs, suggesting that stronger connectivity is required when executing more demanding cognitive control processes [29, 63, 64]. Thus, the reduction of connectivity from the right thalamus to the dACC/pre-SMA observed in the present study indicates that less neural connectivity is required to complete the same domain-general task and achieve similar behavioral performance after language switching training. This finding is also in line with Zhang et al. [31] ERP results, which indicate that language switching training improves the proactive aspect of domain-general cognitive control, i.e., preparatory goal maintenance before target presentation. More specifically, Zhang and colleagues [31] found that the magnitude of the N2 component in cue-locked ERPs was enlarged after training in the experimental group only. In ERP literature, an enlarged N2 has been linked to more cognitive resources allocated for cognitive control processes, such as cue detection, conflict resolution, and inhibition of irrelevant information, and the neural generator of the N2 component is located in the ACC [65, 66]. Therefore, the increased N2 in the cue phase has been interpreted as evidence suggesting that language training enhanced proactive domain-general cognitive control. Showing reduced connection from the right thalamus to the dACC/pre-SMA induced by training, the current results provided further evidence for the impact of language switching training on domain-general cognitive control. During language switching at the training phase, participants needed to frequently and intensely resolve conflicts from cross-language activation in order to select an appropriate response. Previous studies documented that daily language switching experience shapes functional connectivity related to cognitive control [19, 21, 35, 36]. For instance, bilinguals with more frequent switching experience showed stronger functional connectivity between ACC and bilateral putamen, which was correlated with proactive domain-general cognitive control and was also shown to be critical for language control [24, 67]. Compared with natural language switching context, switching in response to a completely artificial cue in the laboratory is more effortful and requires more intense engagement of language control networks, including the DLPFC and ACC [68]. Training protocol in the present study focused on cued and unpredictable switching process and showed reduced switch costs across eight training days, indicating improvement of language control with intensive exercising of language control [48]. Moreover, such experience with conflict resolution and response selection,
especially cued triggered process, involved in language switching changed neural correlated underlying domain-general cognitive control with reduced connectivity from the right thalamus to the dACC/pre-SMA.

One possible underlying reason for such a transfer effect is that shared cognitive processes and common brain networks are involved in both language control and domain-general control [69, 70]. It has been suggested that since bilingual language control and domain-general cognitive control share highly similar brain circuits, these two cognitive processes are highly likely to impact each other [34, 53]. Indeed, many previous studies have shown that bilingual experience shapes both cognitive and neural mechanisms of non-linguistic cognitive control [71–75], implicating that the two types of control have at least some overlap with each other. The current findings offer more direct support for the overlap between language control and domain-general cognitive control from the perspective of training.

As discussed in Introduction, inconsistent results have been obtained in previous studies on bilingual effects on executive functions by comparing monolinguals and bilinguals with various measures such as behavioral performance, electrophysiological responses and neural activation patterns (see [76] for a recent review). It has been proposed that one possible reason for the mixed evidence reported was the dichotomous categorization of bilinguals vs. monolinguals, without the consideration of the heterogeneous profiles of the bilinguals under investigation [21, 23]. Recently, growing research interests have been drawn on investigating the potentially different roles of various bilingual language experiences on cognition and brain plasticity. The training protocol provides a valuable means to determine the potential causal roles of those aspects in modulating cognition and brain [29, 77]. Focusing on the aspect of language switching experience, the current training study provided direct evidence that bilingual language switching experience reduces the neural costs required when performing domain-general cognitive tasks. It has been proposed that language switching, particularly cued language switching, poses extra demands on language control and domain-general control, such as maintaining goals, monitoring conflicts, detecting cues, disengaging from a previous language, engaging a new language [28, 68, 78]. Our results indicate that intensively meeting such control demands during language switching training leads to improved domain-general control abilities. Thus, the current data provide novel evidence for the effect of language switching on cognition and brain plasticity from the perspective of effective brain connectivity. This finding also extends the statement that sustained bilingual experience confers neural adaptations towards increased efficiency [26, 27] by demonstrating the effect of shorter-term language switching training.

Our behavioral results did not reveal significant transfer effect from language-switching training to domain-general cognitive control. We speculate that this could be attributed to the long response stimulus intervals (RSIs) used for the purpose of fMRI scanning. As shown in previous studies [79, 80], longer RSIs cause the sequential congruency effect reflecting conflict control adaption to reduce or even disappear in behavioral performance. As the RSIs in the present study were relatively long (range = 1s to 4s), it is probable that the long RSIs allowed the participants to recover from the influence exerted by the previous trial in the behavioral data. Another possibility for the divergence between our behavioral data and fMRI data and is that the latter is be more sensitive. Such discrepancies have been documented in previous studies testing bilingual effects [9]. Thus, the training effects in our functional connectivity data further suggests that fMRI provides more sensitive measures in detecting the underlying mechanism of bilingual cognitive control than behavioral indices (see [81] for similar discussions). We recognize that one limitation of the current study is that the euSEM analysis cannot generate two independent networks for switch and non-switch conditions. Therefore, we
couldn’t examine any specific effect of language switching training on different conditions in the domain-general cognitive control.

In conclusion, our results demonstrated that short-term language switching training modulated the functional organization of non-linguistic cognitive control network. The cross-domain neural plasticity was predominately exhibited in the reduced connection from the right thalamus to the dACC/pre-SMA. The functional reorganization of the cognitive control network provides direct evidence for the contribution of short-term language switching experience in shaping non-linguistic cognitive control. It will be interesting to further investigate how bilinguals’ prior language experience such as daily switching experience and L2 age of acquisition will function with the network reorganization in the future studies.

Acknowledgments
We thank Can Liu and Ran Wang for their help with data collection, and thank Dr. Eric Pelzel for proofreading the manuscript.

Author Contributions
Conceptualization: Taomei Guo.
Data curation: Zhaoqi Zhang, Shuhua Li.
Formal analysis: Mo Chen, Fengyang Ma, Junjie Wu.
Funding acquisition: Chunming Lu, Taomei Guo.
Investigation: Mo Chen, Zhaoqi Zhang, Man Zhang, Junjie Wu, Taomei Guo.
Project administration: Chunming Lu, Taomei Guo.
Visualization: Mo Chen, Zhaoqi Zhang.
Writing – original draft: Mo Chen, Fengyang Ma, Zhaoqi Zhang, Taomei Guo.
Writing – review & editing: Mo Chen, Fengyang Ma, Zhaoqi Zhang, Man Zhang, Qiming Yuan, Junjie Wu, Chunming Lu, Taomei Guo.

References
1. Green DW. Mental control of the bilingual lexico-semantic system. Bilingualism: Language and Cognition. 1998; 1: 67. https://doi.org/10.1017/S1366728998000133
2. Bialystok E, Craik F, Luk G. Cognitive control and lexical access in younger and older bilinguals. J Exp Psychol-Learn Mem Cogn. 2008; 34: 859–873. https://doi.org/10.1037/0278-7393.34.4.859 PMID: 18605874
3. Bialystok E. Bilingualism: The good, the bad, and the indifferent. Biling-Lang Cogn. 2009; 12: 3–11. https://doi.org/10.1017/S1366728908003477
4. Paap Kenneth R., Johnson Hunter A., Sawi O. Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. Cortex. 2015; 69: 265–278. https://doi.org/10.1016/j.cortex.2015.04.014 PMID: 26048659
5. Bialystok E, Craik FIM, Klein R, Viswanathan M. Bilingualism, Aging, and Cognitive Control: Evidence From the Simon Task. Psychology and Aging. 2004; 19: 290–303. https://doi.org/10.1037/0882-7974.19.2.290 PMID: 15222822
6. Warmington MA, Kandru-Pothineni S, Hitch GJ. Novel-word learning, executive control and working memory: A bilingual advantage. Bilingualism: language and Cognition. 2019; 22: 763–782.
7. Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Scoio P, Keim R, et al. Bilingualism Tunes the Anterior Cingulate Cortex for Conflict Monitoring. Cerebral Cortex. 2011; 22: 2076–2086. https://doi.org/10.1093/cercor/bhr287 PMID: 22038906
8. Bialystok E, Craik FIM, Grady C, Chau W, Ishii R, Gunji A, et al. Effect of bilingualism on cognitive control in the Simon task: evidence from MEG. NeuroImage. 2005; 24: 40–49. https://doi.org/10.1016/j.neuroimage.2004.09.044 PMID: 15588595

9. DeLuca V, Rothman J, Bialystok E, Pliatsikas C. Duration and extent of bilingual experience modulate neurocognitive outcomes. NeuroImage. 2020; 204: 116222. https://doi.org/10.1016/j.neuroimage.2019.116222 PMID: 31557543

10. Garbin G, Sanjuan A, Forn C, Bustamante JC, Rodríguez-Pujadas A, Belloch V, et al. Bridging language and attention: Brain basis of the impact of bilingualism on cognitive control. NeuroImage. 2010; 53: 1272–1278. https://doi.org/10.1016/j.neuroimage.2010.05.078 PMID: 20558314

11. Luk G, Anderson JAE, Craik FIM, Grady C, Bialystok E. Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. Brain and Cognition. 2011; 74: 347–357. https://doi.org/10.1016/j.bandc.2011.05.004 PMID: 21386397

12. Yamasaki BL, Stocco A, Liu AS, Prat CS. Effects of bilingual language experience on basal ganglia computations: A dynamic causal modeling test of the conditional routing model. Brain and Language. 2019; 197: 104665. https://doi.org/10.1016/j.bandl.2019.104665 PMID: 31470347

13. Rodriguez-Pujadas A, Sanjuán A, Ventura-Campos N, Román P, Martin C, Barceló F, et al. Bilinguals Use Language-Control Brain Areas More Than Monolinguals to Perform Non-Linguistic Switching Tasks. Garcia AV, editor. PLoS ONE. 2013; 8: e73028. https://doi.org/10.1371/journal.pone.0073028 PMID: 24058456

14. Waldke KE, Badzakova-Trajkov G, Park HR, Zheng Y, Neumann D, Zamani Foroushani N. The cognitive and neural correlates of written language: a selective review of bilingualism. Journal of the Royal Society of New Zealand. 2020; 1–16.

15. Gold BT, Kim C, Johnson NF, Kryscio RJ, Smith CD. Lifelong Bilingualism Maintains Neural Efficiency for Cognitive Control in Aging. Journal of Neuroscience. 2013; 33: 387–396. https://doi.org/10.1523/JNEUROSCI.3837-12.2013 PMID: 23303919

16. Lehtonen M, Soveri A, Laine A, Jarvenpaä J, de Bruin A, Antfolk J. Is Bilingualism Associated With Enhanced Executive Functioning in Adults? A Meta-Analytic Review. Psychol Bull. 2018; 144: 394–425. https://doi.org/10.1037/bul0000142 PMID: 29494195

17. Ross J, Melinger A. Bilingual advantage, bidialectal advantage or neither? Comparing performance across three tests of executive function in middle childhood. Developmental science. 2017; 20: e12405. https://doi.org/10.1111/desc.12405 PMID: 27684381

18. Surraín S, Luk G. Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005–2015. Bilingualism: Language and Cognition. 2019; 22: 401–415.

19. Guilfer JW, Chai XJ, Whitford V, Pinneva I, Baum S, Klein D, et al. Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. Neuropsychologia. 2018; 117: 123–134. https://doi.org/10.1016/j.neuropsychologia.2018.04.037 PMID: 29727624

20. Mouthon M, Khateb A, Lazeyras F, Pegna AJ, Lee-Jahnke H, Lehr C, et al. Second-language proficiency modulates the brain language control network in bilingual translators: an event-related fMRI study. Bilingualism: Language and Cognition. 2020; 23: 251–264.

21. Sulípizio S, Del Maschio N, Del Mauro G, Fedeli D, Abutalebi J. Bilingualism as a gradient measure modulates functional connectivity of language and control networks. Neuroimage. 2020; 205: 116306. https://doi.org/10.1016/j.neuroimage.2019.116306 PMID: 31654763

22. Yamasaki BL, Stocco A, Prat CS. Relating individual differences in bilingual language experiences to executive attention. Lang Cogn Neurosci. 2018; 33: 1128–1151. https://doi.org/10.1080/23273798.2018.1448092

23. Leivada E, Westergaard M, Duñabeitia JA, Rothman J. On the phantom-like appearance of bilingualism effects on neurocognition:(How) should we proceed? Bilingualism: Language and Cognition. 2021; 24: 197–210.

24. Abutalebi J, Green DW. Neuroimaging of language control in bilinguals: neural adaptation and reserve. Bilingualism: Language and Cognition. 2016; 19: 689–698. https://doi.org/10.1017/S1366728916000223

25. DeLuca V, Rothman J, Bialystok E, Pliatsikas C. Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. COGNITIVE SCIENCES. 2019; 10. https://doi.org/10.1073/pnas.1811513116 PMID: 30914463

26. Grundy JG, Anderson JAE, Bialystok E. Neural correlates of cognitive processing in monolinguals and bilinguals: Neural correlates of bilingualism. Annals of the New York Academy of Sciences. 2017; 1396: 183–201. https://doi.org/10.1111/nyas.13333 PMID: 28415142
27. Platsikas C. Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. Bilingualism. 2020; 23: 459–471. https://doi.org/10.1017/S1366728919000130
28. Green DW, Abutalebi J. Language control in bilinguals: The adaptive control hypothesis. Journal of Cognitive Psychology. 2013; 25: 515–530. https://doi.org/10.1080/20445911.2013.796377 PMID: 25077013
29. Blanco-Ellorrieta E, Pylkkänen L. Ecological Validity in Bilingualism Research and the Bilingual Advantage. Trends in Cognitive Sciences. 2018; 22: 1117–1126. https://doi.org/10.1016/j.tics.2018.10.001 PMID: 30449317
30. Janus M, Lee Y, Moreno S, Bialystok E. Effects of short-term music and second-language training on executive control. Journal of Experimental Child Psychology. 2016; 144: 84–97. https://doi.org/10.1016/j.jecp.2015.11.009 PMID: 25077013
31. Zhang H, Kang C, Wu Y, Ma F, Guo T. Improving proactive control with training on language switching in bilinguals. Neuroreport. 2015; 26: 354–359. https://doi.org/10.1097/WNR.0000000000000353 PMID: 25756906
32. Ma F, Li S, Guo T. Reactive and proactive control in bilingual word production: An investigation of influential factors. Journal of Memory and Language. 2016; 86: 35–59.
33. Timmer K, Calabria M, Costa A. Non-linguistic effects of language switching training. Cognition. 2019; 182: 14–24. https://doi.org/10.1016/j.cognition.2018.09.001 PMID: 30212652
34. Wu J, Yang J, Chen M, Li S, Zhang Z, Kang C, et al. Brain network reconfiguration for language and domain-general cognitive control in bilinguals. Neuroimage. 2019; 199: 454–465. https://doi.org/10.1016/j.neuroimage.2019.06.022 PMID: 31200066
35. Becker M, Schubert T, Strobach T, Gallinat J, Kühn S. Simultaneous interpreters vs. professional multilingual controls: Group differences in cognitive control as well as brain structure and function. Neuroimage. 2016; 134: 250–260. https://doi.org/10.1016/j.neuroimage.2016.03.079 PMID: 27085505
36. Grady CL, Luk G, Craik FIM, Bialystok E. Brain network activity in monolingual and bilingual older adults. Neuropsychologia. 2015; 66: 170–181. https://doi.org/10.1016/j.neuropsychologia.2014.10.042 PMID: 25445783
37. Rodríguez-Fornells A, Krämer UM, Lorenzo-Seva U, Festman J, Münte TF. Self-Assessment of Individual Differences in Language Switching. Front Psychology. 2012; 2. https://doi.org/10.3389/fpsyg.2011.00388 PMID: 22291668
38. Snodgrass J, Vanderwart M. Standardized Set of 260 Pictures—Norms for Name Agreement, Image Agreement, Familiarity, and Visual Complexity. Journal of Experimental Psychology-Human Learning and Memory. 1980; 6: 174–215. https://doi.org/10.1037/0278-7393.6.2.174 PMID: 7373248
39. Yan C-G, Wang X-D, Zuo X-N, Zang Y-F. DPABI: Data Processing & Analysis for (Resting-State) Brain Imaging. Neuroinform. 2016; 14: 339–351. https://doi.org/10.1007/s12021-016-9299-4 PMID: 27075850
40. Gates KM, Molenaar PCM. Group search algorithm recovers effective connectivity maps for individuals in homogeneous and heterogeneous samples. Neuroimage. 2012; 63: 310–319. https://doi.org/10.1016/j.neuroimage.2012.06.026 PMID: 22732562
41. Smith SM, Miller KL, Salimi-Khorshidi G, Webster M, Beckmann CF, Nichols TE, et al. Network modeling methods for FMRI. Neuroimage. 2011; 54: 875–891. https://doi.org/10.1016/j.neuroimage.2010.08.063 PMID: 20817103
42. Hillary FG, Medaglia JD, Gates KM, Molenaar PC, Good DC. Examining network dynamics after traumatic brain injury using the extended unified SEM approach. Brain Imaging and Behavior. 2014; 8: 435–445. https://doi.org/10.1007/s11682-012-9205-0 PMID: 23138853
43. Yang J, Gates KM, Molenaar P, Li P. Neural changes underlying successful second language word learning: An fMRI study. Journal of Neurolinguistics. 2015; 33: 29–49. https://doi.org/10.1016/j.jneuroling.2014.09.004
44. Younger JW, Tucker-Drob E, Booth JR. Longitudinal changes in reading network connectivity related to skill improvement. Neuroimage. 2017; 158: 90–98. https://doi.org/10.1016/j.neuroimage.2017.06.044 PMID: 28645843
45. Rubinov M, Ypma RJF, Watson C, Bullmore ET. Wiring cost and topological participation of the mouse brain connectome. Proc Natl Acad Sci USA. 2015; 112: 10032–10037. https://doi.org/10.1073/pnas.1420315112 PMID: 26216962
46. Newman MEJ. Modularity and community structure in networks. Proceedings of the National Academy of Sciences. 2006; 103: 8577–8582. https://doi.org/10.1073/pnas.0601602103 PMID: 16723398
47. Fornito A, Zalesky A, Bullmore E. Fundamentals of brain network analysis. Academic Press; 2016.
48. Kang C, Fu Y, Wu J, Ma F, Lu C, Guo T. Short-term language switching training tunes the neural correlates of cognitive control in bilingual language production: Language Training Modulates Cognitive Control. Human Brain Mapping. 2017; 38: 5859–5870. https://doi.org/10.1002/hbm.23765 PMID: 28868623

49. Xia M, Wang J, He Y. BrainNet Viewer: A Network Visualization Tool for Human Brain Connectomics. PLoS One. 2013; 8: e68910. https://doi.org/10.1371/journal.pone.0068910 PMID: 23861951

50. Marek S, Hwang K, Foran W, Hallquist MN, Luna B. The Contribution of Network Organization and Integration to the Development of Cognitive Control. Posner M, editor. PLoS Biol. 2015; 13: e1002328. https://doi.org/10.1371/journal.pbio.1002328 PMID: 26713863

51. Sadaghiani S, D’Esposito M. Functional Characterization of the Cingulo-Opercular Network in the Maintenance of Tonic Alertness. Cereb Cortex. 2015; 25: 2763–2773. https://doi.org/10.1093/cercor/bhu072 PMID: 24770711

52. Braver TS, Barch DM, Gray JR, Molfese DL, Snyder A. Anterior cingulate cortex and response conflict: Effects of frequency, inhibition and errors. Cereb Cortex. 2001; 11: 825–836. https://doi.org/10.1093/cercor/11.9.825 PMID: 11532888

53. De Baene W, Duyck W, Brass M, Carreiras M. Brain Circuit for Cognitive Control Is Shared by Task and Language Switching. Journal of Cognitive Neuroscience. 2015; 27: 1752–1765. https://doi.org/10.1162/jocn_a_00817 PMID: 25901448

54. Shenhav A, Botvinick MM, Cohen JD. The Expected Value of Control: An Integrative Theory of Anterior Cingulate Cortex Function. Neuron. 2013; 79: 217–240. https://doi.org/10.1016/j.neuron.2013.07.007 PMID: 23889930

55. Hsu T-Y, Tseng L-Y, Yu J-X, Kuo W-J, Hung DL, Tseng OJL, et al. Modulating inhibitory control with direct current stimulation of the superior medial frontal cortex. NeuroImage. 2011; 56: 2249–2257. https://doi.org/10.1016/j.neuroimage.2011.03.059 PMID: 21459149

56. Jacobson L, Javitt DC, Lavidor M. Activation of Inhibition: Diminishing Impulsive Behavior by Direct Current Stimulation over the Inferior Frontal Gyrus. J Cogn Neuroscience. 2011; 23: 3380–3387. https://doi.org/10.1162/jocn_a_00020 PMID: 21452949

57. Rushworth MFS, Hadland KA, Paus T, Sipila PK. Role of the Human Medial Frontal Cortex in Task Switching: A Combined fMRI and TMS Study. Journal of Neurophysiology. 2002; 87: 2577–2592. https://doi.org/10.1152/jn.2002.87.5.2577 PMID: 11976394

58. Taylor PCJ, Nobre AC, Rushworth MFS. Subsecond Changes in Top Down Control Exerted by Human Medial Frontal Cortex during Conflict and Action Selection: A Combined Transcranial Magnetic Stimulation Electroencephalography Study. Journal of Neuroscience. 2007; 27: 11343–11353. https://doi.org/10.1523/jneurosci.2877-07.2007 PMID: 17942729

59. Yu J, Tseng P, Hung DL, Wu S-W, Juan C-H. Brain stimulation improves cognitive control by modulating medial-frontal activity and preSMA-vmPFC functional connectivity: Brain Stimulation Improves Cognitive Control. Human Brain Mapping. 2015; 36: 4004–4015. https://doi.org/10.1002/hbm.22893 PMID: 26248582

60. Minzenberg MJ, Laird AR, Thelen S, Carter CS, Glahn DC. Meta-analysis of 41 Functional Neuroimaging Studies of Executive Function in Schizophrenia. Arch Gen Psychiatry. 2009; 66: 811–822. https://doi.org/10.1001/archgenpsychiatry.2009.91 PMID: 19652121

61. Chen T, Becker B, Camilleri J, Wang L, Yu S, Eichhoff SB, et al. A domain-general brain network underlying emotional and cognitive interference processing: evidence from coordinate-based and functional connectivity meta-analyses. Brain Structure and Function. 2018; 223: 3813–3838. https://doi.org/10.1007/s00429-018-1727-9 PMID: 30083997

62. Kobayashi Y. Cingulate gyrus: cortical architecture and connections. Brain and nerve = Shinkei kenkyu no shinpo. 2011; 63: 473–82. PMID: 21515927

63. Cocchi L, Halford GS, Zalesky A, Harding IH, Ramm BJ, Cutmore T, et al. Complexity in Relationa l Processing Predicts Changes in Functional Brain Network Dynamics. Cereb Cortex. 2014; 24: 2283–2308. https://doi.org/10.1093/cercor/bht075 PMID: 23563963

64. Harding IH, Yücel M, Harrison BJ, Pantelis C, Breakspear M. Effective connectivity within the frontoparietal control network differentiates cognitive control and working memory. NeuroImage. 2015; 106: 144–153. https://doi.org/10.1016/j.neuroimage.2014.11.039 PMID: 25463464

65. Bokura H, Yamaguchi S, Kobayashi S. Electrophysiological correlates for response inhibition in a Go/NoGo task. Clin Neurophysiol. 2001; 112: 2224–2232. https://doi.org/10.1016/s1388-2457(01)00691-5 PMID: 11738192

66. Nieuwenhuis S, Yeung N, van den Wildenberg W, Ridderinkhof KR. Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. Cogn Affect Behav Neurosci. 2003; 3: 17–26. https://doi.org/10.3758/cabn.3.1.17 PMID: 12822595
67. Abutalebi J, Della Rosa PA, Ding G, Weekes B, Costa A, Green DW. Language proficiency modulates the engagement of cognitive control areas in multilinguals. Cortex. 2013; 49: 905–911. https://doi.org/10.1016/j.cortex.2012.08.018 PMID: 23021069

68. Blanco-Ellorrieta E, Pykkänen L. Bilingual Language Switching in the Laboratory versus in the Wild: The Spatiotemporal Dynamics of Adaptive Language Control. The Journal of Neuroscience. 2017; 37: 9022–9036. https://doi.org/10.1523/JNEUROSCI.0553-17.2017 PMID: 28821648

69. Dahlén E, Neely AS, Larsson A, Backman L, Nyberg L. Transfer of Learning After Updating Training Mediated by the Striatum. Science. 2008; 320: 1510–1512. https://doi.org/10.1126/science.1155466 PMID: 18546560

70. Hussey EK, Harbison JI, Teubner-Rhodes SE, Mishler A, Velnoskey K, Novick JM. Memory and language improvements following cognitive control training. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2017; 43: 23–58. https://doi.org/10.1037/xlm0000283 PMID: 27414956

71. Anderson JAE, Chung-Fat-Yim A, Bellana B, Luk G, Bialystok E. Language and cognitive control network in bilinguals and monolinguals. Neuropsychologia. 2018; 117: 352–363. https://doi.org/10.1016/j.neuropsychologia.2018.06.023 PMID: 29959966

72. Becker M, Schubert T, Strobach T, Gallinat J, Kühn S. Simultaneous interpreters vs. professional multilinguals: Group differences in cognitive control as well as brain structure and function. NeuroImage. 2016; 134: 250–260. https://doi.org/10.1016/j.neuroimage.2016.03.079 PMID: 27085505

73. Elmer S, Meyer M, Marrama L, Jäncke L. Intensive language training and attention modulate the involvement of fronto-parietal regions during a non-verbal auditory discrimination task: Intensive language training and attention modulate the involvement of fronto-parietal regions. European Journal of Neuroscience. 2011; 34: 165–175. https://doi.org/10.1111/j.1460-9568.2011.07728.x PMID: 21649758

74. Pot A, Keijzer M, de Bot K. Intensity of Multilingual Language Use Predicts Cognitive Performance in Some Multilingual Older Adults. Brain Sciences. 2018; 8: 92. https://doi.org/10.3390/brainsci8050092 PMID: 29783764

75. Van de Putte E, De Baene W, Garcia-Penton L, Woumans E, Dijkgraaf A, Duyck W. Anatomical and functional changes in the brain after simultaneous interpreting training: A longitudinal study. Cortex. 2018; 99: 243–257. https://doi.org/10.1016/j.cortex.2017.11.024 PMID: 29291929

76. van den Noort M, Struys E, Bosch P, Jaswetz L, Perriard B, Yeo S, et al. Does the Bilingual Advantage in Cognitive Control Exist and If So, What Are Its Modulating Factors? A Systematic Review. Behav Sci. 2019; 9: 27. https://doi.org/10.3390/bs9030027 PMID: 30871228

77. Bialystok E. The bilingual adaptation: How minds accommodate experience. Psychological Bulletin. 2017; 143: 233–262. https://doi.org/10.1037/bul0000099 PMID: 28230411

78. Blanco-Ellorrieta E, Emmorey K, Pykkänen L. Language switching decomposed through MEG and evidence from bimodal bilinguals. Proceedings of the National Academy of Sciences. 2018; 115: 9708–9713. https://doi.org/10.1073/pnas.1809779115 PMID: 30206151

79. Egner T. Going, going, gone: characterizing the time-course of congruency sequence effects. Frontiers in Psychology. 2010;1.

80. Grundy JG, Chung-Fat-Yim A, Friesen DC, Mak L, Bialystok E. Sequential congruency effects reveal differences in disengagement of attention for monolingual and bilingual young adults. Cognition. 2017; 163: 42–55. https://doi.org/10.1016/j.cognition.2017.02.010 PMID: 28273520

81. Silverstein SM, Berten S, Essex B, All SD, Kasi R, Little DM. Perceptual organization and visual search processes during target detection task performance in schizophrenia, as revealed by fMRI. Neuropsychologia. 2010; 48: 2886–2893. https://doi.org/10.1016/j.neuropsychologia.2010.05.030 PMID: 20678981