

**The cerebellum and cognition: further evidence for its role in language control**

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**Abstract**

The cognitive function of the human cerebellum could be characterized as enigmatic. However, researchers have attempted to detailed the comprehensive role of the cerebellum in several cognitive processes in recent years. Here, using functional magnetic resonance imaging (fMRI) and transcranial direct current stimulation (tDCS), we revealed different functions of bilateral cerebellar lobules in bilingual language production. Specifically, brain activation showed the bilateral posterolateral cerebellum was associated with bilingual language control, and an effective connectivity analysis built brain networks for the interaction between the cerebellum and the cerebral cortex. Furthermore, anodal tDCS over the right cerebellum significantly optimizes language control performance in bilinguals. Together, these results reveal a precise asymmetrical functional distribution of the cerebellum in bilingual language production, suggesting that the right cerebellum is more involved in language control. In contrast, its left counterpart undertakes a computational role in cognitive control function by connecting with more prefrontal, parietal, subcortical brain areas.

**Keywords:** cerebellum, bilingualism, fMRI, brain networks, neuromodulation, tDCS

## Introduction

Despite its relatively small volume, the cerebellum has almost eighty percent of the surface area of the neocortex (Serenio et al. 2020) and has more neurons than any other part of the brain (Williams and Herrup 1988). Although it has historically been considered as an ad hoc neural apparatus for motor control that manages the coordination, stabilization, and automatism of movement in the human neural system (Kawato 1999; Manto et al. 2012), in the past few decades, the focus of cerebellar studies has switched toward discovering its role in other cognitive and affective functions. Specifically, cerebellar activation has been observed in tasks without overt motor function such as attention (Kellermann et al. 2012), language (Frings et al. 2006), executive function (D'Mello et al. 2020), and emotion (for review, see Strick et al. 2009; Baumann and Mattingley 2012). In addition, studies on cerebellar deficit have also supported the role of the cerebellum in cognition, such as language (Fiez et al. 1992) and executive functions (Karatekin et al. 2000).

A further important question is the functional lateralization of the cerebellum, i.e., whether the left and the right cerebellum are involved in distinct cognitive functions. It has been shown that the left cerebellum is engaged in cognitive spatial operations (Van Mier et al. 1998; Imamizu et al. 2003), whereas the right cerebellum is associated with language processing (Liu et al. 2000; Marien et al. 2001; Marien et al. 2014). Recent studies have further revealed that cerebellar functional asymmetry originates from a more complex activity pattern of cerebellar subregions. Specifically, sensorimotor function mainly activates the anterior lobe, whereas other cognitive functions trigger the activation of posterior lobules (Stoodley and Schmahmann 2009; Stoodley et al. 2010, 2012). However, little is known with regards to how distinct cerebellar subregions interact with the cerebral cortex to support these functions. Hence, the cerebellum is supposed to play a simple role in local neural computations, and its cognitive functions can be defined by its efferent and afferent connections (Ramnani 2006; Eccles 2013).

Hence, beyond addressing the function of different hemispheres and lobules of the cerebellum, previous studies have discovered that different subregions of the cerebellum both functionally and structurally connect to different areas in the cerebral cortex (Krienen and Buckner 2009; Buckner et al. 2011; Ji et al. 2019). These coupled areas co-activate in cognitive tasks (Stoodley et al. 2010, 2012) and function as a topographically organized network (Kellermann et al. 2012).

Language, as one of the most complex cognitive functions, relies on not only sophisticated cerebral cortical organization (see Price 2012 for a review) but also the cortical organization of the cerebellum. The cerebellar activation in speech production was first discovered by Petersen et al. (1988). They reported activation in the right lateral cerebellum when participants are producing words in a verb generation task. Since then, accumulated neuroimaging results uncovered that the activation of the right posterior cerebellum is activated for language production, whereas its left counterpart may potentially contribute to the executive function during language production (for a review, see Stoodley and Schmahmann 2009).

In the language domain, complementary to traditional language production tasks, the language switching task (Meuter and Allport 1999) requires bilingual participants to switch between two languages. Such a process triggers cross-language interference, so language control is recruited to eliminate the interference during language production (Green 1998). In a typical language switching task, participants are asked to name pictures in their native language (L1) or second language (L2) according to a specific type of cue. The trial named in the same language as the former one is characterized as a non-switch trial, whereas the trial named in a different language from the former one is characterized as a switch trial. Previous studies have found that language switch trials induce longer response times with an increased error rate than non-switch trials. Therefore, the language switch cost (i.e., the response time/error rate difference between language switch and non-switch trials) can be characterized as a behavioral measure for bilingual language control (Bialystok et al. 2006; Bialystok et al. 2007).

Previous neuroimaging studies have found that switch trials more strongly activate some cortical areas, including the left medial frontal gyrus (LMFG), dorsal anterior cingulate cortex/pre-supplementary motor area (dACC/pre-SMA), right inferior frontal gyrus (RIFG) (Hernandez et al. 2000; Hernandez et al. 2001; Rodriguez-Fornells et al. 2005; Abutalebi, Della Rosa, Ding, et al. 2013; Abutalebi, Della Rosa, Gonzaga, et al. 2013; Branzi et al. 2016). Stronger activation from subcortical brain areas, such as the left caudate nucleus and the thalamus, are also observed (Abutalebi, Della Rosa, Gonzaga, et al. 2013; Wu et al. 2019). Besides the stronger activity in the cerebral cortex, several neuroimaging studies have revealed cerebellar activation in the bilateral lobules VI, left Crus I, and left lobule VIII associated with language control (Price et al. 1999; Wang et al. 2007; Guo et al. 2011; de Bruin et al. 2014; De Baene et al. 2015; Fu et al. 2017; Reverberi et al. 2018; Wu et al. 2019. Names of cerebellar subregions were determined by the MNI coordinates reported in referenced articles.). In a recent meta-analysis by Sulpizio et al. (2020), stronger activation in the left Crus I was associated with bilingual language switching. Furthermore, some other studies have shown that the cerebellum can modulate the function of its cerebral counterparts through structural connections (Bostan et al. 2010, 2013), such as the right inferior frontal gyrus (Aron et al. 2007), and the caudate nucleus (via the thalamus, Bostan et al. 2010). Taking these findings together, Abutalebi and Green (2016) proposed a hypothesis-driven model for bilingual language control based on brain regions reported in structural and functional neuroimaging studies and extrapolated a network diagram. Specifically, this network model consists of the dorsal anterior cingulate cortex/pre-supplementary motor area (dACC/pre-SMA), left prefrontal cortex, right inferior frontal gyrus, and bilateral inferior parietal lobe, thalamus, and the basal ganglia (caudate/putamen) associated with language control. The network also receives and transform control signals to the cerebellum through the basal ganglia. Based on this hypothesis, our previous studies (Wu et al. 2019; Yuan et al. 2021) revealed empirical effective networks that

consist of intracerebral and fronto-cerebellar connections with the left SMA (or dACC/pre-SMA) centered. Specifically, in the network of Wu et al. (2019), the cerebellum is connected with frontal areas via the thalamus and the parietal cortex, whereas in the network of Yuan et al. (2021), the cerebellum is connected with the left precentral gyrus.

However, the specific role of the cerebellum in bilingual language control is still far from understood. Although neuroimaging results have supported the claim that language control is cerebellar-dependent, previous studies have not yet divided the cerebellum into subregions, which would potentially belie the discovery of hierarchical processing pathways within the cerebellum. Furthermore, most studies on cerebro-cerebellar mapping have examined resting-state functionally connectivity and have not provided evidence as to how the cerebellum and the cerebral cortex functionally coordinate in response to the task requirement. Even in a recent meta-analytical study by Tao et al. (2021), the role of the cerebellum in language control was observed but not clearly discussed. Also, previous studies on task-state effective connectivity have mainly treated the cerebellum as a whole entity (e.g., Wu et al. 2019; Yuan et al. 2021), which leads to the lack of observation of specific functions in different cerebellar subregions.

Therefore, the aims of the present study are two folds. The first aim is to elucidate whether there are distinct cerebellar contributions to language control by investigating the activation pattern within the cerebellar cortex. The second aim is to construct a cerebro-cerebellar network with both cerebellar and cerebral areas and to examine how individual task performance moderates the network and further affects bilingual language control.

In Experiment 1, Chinese-English bilinguals were instructed to perform a cued picture naming task while being scanned with MRI. To reach the first aim, we measured cerebellar activation using the spatially unbiased SUIT atlas (Diedrichsen 2006) to overcome the relatively low functional SNR (signal-to-noise ratio) in the cerebellum (Pfaffenrot et al. 2018).

Moreover, to investigate the coordination between the cerebellum and the cerebral cortex, we performed an effective connectivity analysis to construct a task-state cerebro-cerebellar network by using the euSEM approach (Gates et al. 2011). We also adopted specification curve analysis (SCA, Simonsohn et al. 2020) to assess how cerebro-cerebellar connectivity affects individual language control performance to alleviate decision biases. We hypothesized that, like the cerebral cortex, the posterolateral cerebellum would show discrete cortical organization for language control. In addition, the cerebral and cerebellar areas would assemble as intracerebral and intracerebellar networks, which further coordinate via critical cerebrocerebellar pathways. Moreover, we also expected to observe that the features of networks would be moderated by task performance.

In addition, to further investigate the causal role of the cerebellum in language control and its functional lateralization, in Experiment 2, we utilized the anodal transcranial direct current stimulation (tDCS) to modulate neural activity in the cerebellum and to examine its layover effect in the same language switching task. The cerebellar tDCS is a non-invasive and effective tool in stimulating cerebellar excitability (Grimaldi et al. 2014; Grimaldi et al. 2016), and it has been adopted in modulating a variety of cognitive functions such as attention (Ferrucci et al. 2008), language (D'Mello et al. 2017), and emotion (Ferrucci et al. 2012). In two recent studies, the tDCS has been adopted to stimulate the dorsolateral prefrontal cortex to modulate its language control functions (Tong et al. 2020; Vaughn et al. 2020). To a step further, the current study is the first one to modulate the cerebellar activity in language control.

A group of participants from the same subject pool were recruited and randomly assigned to three stimulation conditions, i.e., anodal stimulation to the left posterolateral cerebellum, anodal stimulation to the right posterolateral cerebellum, and sham stimulation, in a double-blind, between-subjects, and sham-controlled design. Participants were required to perform the same language switching task before and after the stimulation. Different sets of pictures were

used for the two sessions in order to avoid any repetition effects induced by the same sets of materials (e.g., Wu et al. 2018). Participants were also requested to complete a digit naming task during stimulation to strengthen the functional effect of current stimulation (Grimaldi et al. 2016). We aimed to investigate the causal relationship between the activation of the posterolateral cerebellum and language control. According to previous results, we hypothesized that the anodal cerebellar tDCS on the left and the right hemispheres of the cerebellum would result in different behavioral outcomes.

## **Experiment 1 (fMRI)**

### **Materials and Methods**

#### ***Participants***

For Experiment 1, the primary statistical contrast is a paired sample *t*-test between two conditions. Therefore, we followed a rule of thumb in fMRI studies that a minimum number of 20 (or 24) participants (Desmond and Glover 2002; Thirion et al. 2007) would be appropriate to achieve a power of more than 80%. Hence, thirty-eight Chinese-English bilinguals (25 females, age:  $M = 22.5$  years,  $SD = 2.1$  years) were recruited in the experiment. All participants were right-handed, with normal or corrected-to-normal vision, and reported no neurological disorders. They were all native Chinese speakers and reported learning English at an average age of 9.45 years ( $SD = 2.45$  years, range: 3-16 years). All participants passed the College English Test Band 4 ( $M = 540$ ,  $SD = 44$ , full score = 710), an obligatory normalized English test for college students in China. They also self-rated their language proficiency in both languages on a 10-point scale for listening, speaking, reading, and writing. Their self-rating scores in Chinese ( $M = 7.93$ ,  $SD = 1.15$ ) are significantly higher than those in English ( $M = 5.61$ ,  $SD = 1.28$ ;  $t(37) = 11.31$ ,  $p < 0.001$ ), indicating that they are Chinese-dominant bilinguals.



**Table 1** Behavioral measures of the Experiment 1

<b>Behavioral measures</b>	<i>N</i>	Age	CET-4	L2 AoA	L1 self-rating score	L2 self-rating score
<b>Value</b>	38 (25 females)	22.5 (2.1)	540 (44)	9.45 (2.45)	7.93 (1.15)	5.61 (1.28)

**Note.** L2 AoA = L2 age of acquisition. Means (standard deviations) of participants.

### *Experimental Design*

Eighty-eight line drawings of common objects were selected from the Snodgrass and Vanderwart (1980) database as the experimental stimuli. Eighty pictures were used for the formal experiment, whereas the other eight pictures were used for the practice session and as fillers. During the experiment, participants were required to name a picture in either Chinese or English according to the color of the picture frames. The cue-language mappings were counterbalanced across participants. The trial type was defined as a switch trial when participants named two consecutive pictures/digits in different languages and a non-switch trial when two consecutive pictures/digits were named in the same language. Each trial started with a fixation cross presented for 300 ms. After a blank screen of 200 ms, a picture with a colored frame was presented for 1 s in the center of the screen.

The current experiment adopted the same protocol as our previous study (Yuan et al. 2021). The institutional review board approved the experiment at Beijing Normal University. All participants signed informed consent before the experiment and received debriefing forms after the experiment. Before completing the formal language switching task, all participants were instructed to familiarize themselves with all experimental line drawings one by one along with their corresponding names in Chinese and English to ensure sufficient familiarization of each item. They also took part in a brief practice session of 16 trials using 8 pictures before MRI scanning. All participants were fixed with a 12-channel head coil to minimize their head

movement. Participants were also required to name the pictures in an overt but relatively soft voice to minimize jaw and tongue movements and avoid head motions.

The formal experiment consisted of four runs of the picture naming task. Each run consisted of 82 trials (40 switch trials, 40 non-switch trials, and 2 filler trials at the beginning). Filler trials were excluded from further analysis due to the magnetic field instability at the start of each scan. An 8-minute anatomical scan was applied afterward. Thus, the whole experiment lasted about 40 minutes. Unfortunately, we could not collect participants' naming responses during scanning due to the loud noise generated by the MRI scanner. Therefore, they were asked to perform the same language switching task in the behavioral laboratory after scanning.

### ***Imaging protocol***

Functional and structural MRI images were collected by a 3T Siemens Trio Tim MRI scanner. The functional scanning with a T2-weighted echo EPI sequence was set according to the following parameters: TR = 2000 ms, TE = 20 ms, flip angle = 90°, FoV = 200 × 200 mm<sup>2</sup>, matrix size = 64 × 64. The parameters of the high-resolution T1-weighted anatomical scan were set as follows: TR = 2530 ms, TE = 3.39 ms, flip angle = 7°, FoV = 256 × 256 mm<sup>2</sup>, matrix size = 256 × 256.

### **Statistical Analysis**

#### ***Analysis of the cerebellar activation***

This analysis aimed to identify the cerebellar activation during the language switching task. The cerebellar images were preprocessed using the Statistical Parametric Mapping Toolbox 12 (SPM12, The Wellcome Centre for Human Neuroimaging, UCL Queen Square Institute of Neurology, London, UK). We discarded the first 4 images related to the 2 filler trials. The remaining images were entered into the formal analyses. First, slice timing correction and the realignment of the functional images were performed (all participants met

the requirement of absolute head motions  $< 2$  mm and  $2^\circ$ ). Then, we set the anatomical scans to the anterior commissure and co-registered the functional images to these anatomical images. Finally, we performed the first-level analysis according to our design matrix (switch  $>$  non-switch) and exported the first-level beta images.

All remaining analyses were conducted using the SUIT toolbox (Diedrichsen 2006). First, we used the SUIT isolate function to isolate the cerebellum from the rest of the brain. Second, we normalized the anatomical images to the SUIT template using a nonlinear deformation provided by the SUIT normalize function. Third, we resliced the functional beta images using the deformation obtained in the previous step and used the SUIT template to exclude activation voxels outside the cerebellum. Finally, we spatially smoothed the resliced images using an FWHM = 6 Gaussian kernel and performed a second-level one-sample  $t$ -test to reach the final  $T$ -map for the cerebellar activation.

### ***Preprocessing of the whole-brain images***

In order to construct a cerebro-cerebellar effective connectivity network, we preprocessed the whole-brain images to discard various artifacts and extracted signals. The preprocessing of the whole-brain images was conducted using the DPABI toolbox (Yan et al. 2016). The first 4 functional images of the 2 filler trials were discarded. The remaining images were preprocessed according to the following protocol: First, slice timing correction and the realignment of the functional images were performed (all participants met the requirement of absolute head motions  $< 2$ mm and  $2^\circ$ ). Second, individual anatomical images were co-registered to the mean functional image. Third, the anatomical images were segmented to gray matter, white matter, and cerebrospinal fluid (Ashburner and Friston 2005). Fourth, we used the Friston-24 parameter model to remove the nuisance signals and regress the data's head motion effects (Friston et al. 1996). The signal of the white matter and the cerebrospinal fluid (CSF) were also regressed out to reduce respiratory and cardiac effects. Fifth, we normalized all images into the

MNI space and resliced them to the resolution of  $3 \times 3 \times 3 \text{ mm}^3$ . Finally, all images were spatially smoothed by an FWHM = 6 mm Gaussian kernel.

### *Effective connectivity analysis*

To construct a cerebro-cerebellar connectivity network, the effective connectivity analysis was performed using the euSEM (Gates et al. 2011) approach, enabling us to build a connectivity map among predefined brain nodes. This connectivity analysis is widely used in functional brain connectivity studies and allows us to perform an effective connectivity analysis without prior theoretical hypotheses (e.g., Hillary et al. 2011; Yang and Li 2012; Yang et al. 2015; Wise Younger et al. 2017; Wu et al. 2019; Wu et al. 2020; Yuan et al. 2021).

**Node selection:** The 5 cerebellar nodes were selected based on the results of cerebellar activation analysis. We drew a sphere with the center of the peak MNI coordinate of the activation cluster and a radius of 6 mm. The 7 cerebral nodes were selected based on Abutalebi and Green (2016) proposed network model by identifying names of brain areas and specifying its cluster using the Human Brainnetome Atlas (Fan et al. 2016): The left medial frontal gyrus (L.MFG, #21, the number labels of the HBA), right inferior frontal gyrus (R.IFG, #38), dorsal anterior cingulate cortex/pre-supplementary motor cortex (dACC/pre-SMA, the combination of #1, #2, #183, and #184), left inferior parietal lobe (L.IPL, #137), left caudate nucleus (L.CN, #227), left thalamus (L.Thal, #245), and the right thalamus (R.Thal, #246). The time series of each node was extracted from the preprocessed data and served for the following connectivity analysis.

**Model selection:** The model selection of the connectivity analysis was conducted by the Group Iterative Multiple Model Estimation (GIMME, Gates and Molenaar 2012). The data processing pipeline was described as follows: First, we applied the Lagrange multiplier equivalents (i.e., modification indices, Sörbom 1989) to identify which connectivity path, if freed, optimally improved model fitting for more than 75% of individuals. Second, the model

was pruned by eliminating connections that were insignificant for 75% of the group after connections were freed (i.e., be estimated from the data). Third, all connections freed at the group level were freed at the individual level in a semi-confirmatory manner. Finally, the model was pruned by eliminating individual-level connections that became insignificant after other individual-level connections were freed. We chose prior reliability to demonstrate the model fit indices so that the two criteria [comparative fit index (CFI)  $\geq 0.95$ ; Tucker-Lewis index (TLI)  $\geq 0.95$ ] were satisfied.

**Core-periphery structure detection:** Furthermore, we performed core-periphery structure detection and calculated global efficiency using the Brain Connectivity Toolbox (Rubinov and Sporns 2010). We also used the core-periphery subdivision algorithm (Rubinov et al. 2015) to divide the connectivity network into a core and a periphery group. This procedure was conducted to maximize the within core-group edges and minimize the within periphery-group edges (Braun et al. 2015), and the core-ness index (Q) was reported to quantify the goodness of the optimal core-periphery subdivision. Next, the global efficiencies of the brain connectivity map were examined at the individual level, which was defined by the average of the inverse shortest path lengths (Rubinov and Sporns 2010).

### *Specification curve analysis*

To further investigate how the brain network is constructed to support behavioral performance, we adopted the specification curve analysis (SCA, Simonsohn et al. 2020). The SCA is a framework of modeling all possible specifications (selection of models with independent, dependent, and control variables) that are theoretically and statistically valid to test a particular research question. Recent studies have highlighted its benefits in neuroimaging studies to provide an unbiased and explicit network to test all 'reasonable' specifications (analytical decisions) to reduce the overall false-positive rate and to strengthen the robustness

of a given finding (Cosme and Lopez 2020; Flournoy et al. 2020; Klapwijk et al. 2021). In the current analysis, rather than specifying a specific neural variable (a particular connectivity strength) to test the neural-behavioral relationships, all connection strengths calculated from the above effective connectivity analysis were put into the SCA.

The SCA was performed with the `specr` package (Masur and Scharkow 2020) in R (The R Foundation). First, we specified the switch cost (i.e., the difference between switch and non-switch trials in terms of response times) in the language switching task as the outcome variable and all connection strengths among 12 brain nodes (24 connections in total) as neural predictors. In addition, participants' demographics (i.e., age and gender), language proficiency (i.e., L1 self-rating scores, L2 self-rating scores, CET-4 scores), and the L2 age of acquisition were set as control variables. In each specification model, a single indicator of a connection strength was set as the predictor of interest, and its association with the outcome was assessed with the change of analytic decisions and covariates included in the model. Subsequently, the standardized regression coefficients for each predictor were calculated and ordered by effect size to plot the specification curve. For each model of specification in the curve, we visualized which connection strength was the predictor of interest and the analytic decision as well as control variables entered in the model. Finally, the median standardized regression coefficient was calculated with the proportion of the statistically significant positive and negative coefficients. The inferential statistics of the regression coefficients were performed by a bootstrapping (1000 times) process that generates confidence intervals around the curve medians and assesses the inconsistency between the observed curve parameters and the null distribution, which assumes no statistically significant relationship in each predictor-outcome pair. The detailed bootstrapping procedure can be viewed in the Supplementary Materials.

## Results

### ***Behavioral results***

Naming data from two participants were lost due to a malfunction of the digital recorder. The following protocol filtered the remaining data of 36 participants: First, response times (RTs) for the incorrect responses were excluded (9.60%). Then RTs below 300 ms and above 2500 ms (0.80%), as well as 2.5 standard deviations shorter or longer than each participant's mean (2.00%) were discarded.

A 2 (language: Chinese & English) \* 2 (condition: switch & non-switch) ANOVA was performed on response times and naming accuracy, respectively. The analysis for naming response times showed that the main effect of language was significant ( $F(1, 35) = 42.057, p < 0.001, \eta_p^2 = 0.546$ ). The main effect of condition was also significant ( $F(1, 35) = 131.163, p < 0.001, \eta_p^2 = 0.789$ ). A significant language \* condition interaction was also observed ( $F(1, 35) = 4.530, p = 0.040, \eta_p^2 = 0.115$ ), indicating that switch costs in L1 were larger than that in L2. In addition, the analysis for accuracy revealed a significant main effect of condition ( $F(1, 35) = 15.687, p < 0.001, \eta_p^2 = 0.309$ ). However, there were no significant main effect of language ( $F(1, 35) = 1.700, p = 0.201, \eta_p^2 = 0.046$ ) and interaction ( $F(1, 35) = 1.020, p = 0.320, \eta_p^2 = 0.028$ ).

### ***Cerebellar activation associated with language control***

As shown in Table 2 and Figure 1, greater activation of bilateral cerebellar lobules VI and VIII was induced by the switch condition compared with the non-switch condition.

**Table 2.** Cerebellar activation of language control (contrast: switch > non-switch)

Region	Cluster size	MNI coordinates (x, y, z)			t value
L.lobule VI (lateral)	332	-36	-50	-29	7.24
L.lobule VI (medial)	106	-4	-66	-15	5.74
L.lobule VIII	406	-20	-62	-51	6.93

R.lobule VI	760	28	-68	-19	7.38
R.lobule VIII	100	30	-58	-53	7.11

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**Note.** L = left, R = right, lateral/medial = lateral/medial surface of the hemisphere.

Uncorrected  $p < 0.001$  at voxel level and GRF-FWE corrected  $p < 0.05$  at cluster level.

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Insert Figure 1 Here

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### ***Cerebro-cerebellar network associated with language control***

Five cerebellar nodes were selected according to the cerebellar activation results. Specifically, the 2 nodes were defined based on the two activated clusters inside the left lobule VI and were marked as L.lobule VI (lateral) and L.lobule VI (medial), respectively. In addition, 7 cerebral nodes were defined by the Human Brainnetome Atlas (Fan et al. 2016) based on Abutalebi and Green (2016).

As shown in Figure 2, euSEM revealed an excellent fitted map with the following fit indices: CFI = 1, TLI = 1. Moreover, the optimal core-periphery subdivision algorithm uncovered that the dACC/pre-SMA and the L.lobule VI (lateral) as the cores of the connectivity network with a core-ness index (Q) of 0.61. The average global efficiency of individual connectivity maps is 0.39. The network can be divided into 3 modules: intracerebral connections, intracerebellar connections, and cerebro-cerebellar connections.

The intracerebral connections consist of connections from the dACC/pre-SMA to the L.MFG, R.IFG, and the L.IPL, connection from the L.MFG to the L.CN, connections from the R.IFG to the L.MFG and the L.Thal, the connection from the L.Thal to the R.Thal, connections



from the R.Thal to the dACC/pre-SMA and the L.CN, and bipolar connection between the L.MFG and the L.IPL.

Additionally, the intracerebellar connections consist of connections from the L.lobule VI (lateral) to the L.lobule VI (medial), L.lobule VIII, R.lobule VI, and the R.lobule VIII, connections from the L.lobule VI (medial) to the L.lobule VIII and the R.lobule VIII, connection from the R.lobule VI to the L.lobule VI (medial), and the connection from the L.lobule VIII to the R.lobule VIII.

Finally, the cerebro-cerebellar connections consist of the bipolar connection between the two cores (i.e., the dACC/pre-SMA and the L.lobule VI (lateral)), the connection from the L.IPL to the L.lobule VI (lateral), the connection from the dACC/pre-SMA to the R.lobule VI, and the connection from the L.lobule VI (medial) to the L.Thal.

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Insert Figure 2 Here

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### ***The specification curve of connection strengths and switch costs***

The specification curve is shown in Figure 3, and the bootstrapped results are shown in Table 3. Only significant specifications are reported in Table 3, whereas bootstrapped results for all specifications can be viewed in the Supplementary Materials. The results showed significant positive relationships between 2 intracerebellar connection (i.e., L.lobule VI (med.) → L.lobule VIII & R.lobule VI → L.lobule VI (med.)) and the switch cost. In addition, significant negative relationships between an intracerebellar connection (i.e., L.lobule VI (lat.)

→ L.lobule VI (med.)) and an intracerebral connection (i.e., L.Thal → R.Thal) with the switch cost of response time were observed.

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 Insert Figure 3 Here  
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**Table 3.** Bootstrapped results of the specification curve analysis

Neural indicators (Connection strengths)	The median standardized regression coefficients		Number of significant positive associations		Number of significant negative associations	
	$\beta$	$p$	$N$	$p$	$N$	$p$
L.lobule VI (med.) → L.lobule VIII	142.3	< 0.001	6	0.003	0	1
R.lobule VI → L.lobule VI (med.)	123.67	< 0.001	8	< 0.001	0	1
L.lobule VI (lat.) → L.lobule VI (med.)	-108.52	< 0.001	0	1	8	< 0.001
L.Thal → R.Thal	-191.2	< 0.001	0	1	6	< 0.001

Note:  $N$  = the number of specification models in each specification curve analysis which the positive/negative regression coefficient is statistically significant at  $p < 0.05$ . The total number of specifications for each indicator is 8. The bootstrapping was performed 1000 times. Brain nodes: L.Thal = left thalamus, R.Thal = right thalamus, L.lobule VI (lat./med.) = left lobule VI (lateral/medial), L.lobule VIII = left lobule VIII, R.lobule VI = right lobule VI. Arrows represent the direction of each connection.

## Experiment 2 (tDCS)

### Materials and Methods

#### *Participants*

The number of participants was predetermined by the statistical power analysis using the G\*Power software (Version 3.1, Faul et al. 2009). The power analysis was set as "A priori, compute required sample size" and the statistical test was set as "ANOVA: Repeated measures, within-between interaction". The power,  $\alpha$ , and the effect size were set as G\*Power default parameters (power = 0.95,  $\alpha$  = 0.05, effect size = 0.25), and the number of groups was set as 3 with 2 repeated measures. The output showed that a minimum total number of 66 participants was required for the current design. Therefore, to satisfy the counterbalance arrangement of the current study, 72 participants (49 females, age:  $M = 21.6$  years,  $SD = 2.0$  years) from the same subject pool were recruited. All participants were right-handed, with normal or corrected-to-normal vision, and reported no neurological disorders. Data from 5 participants were excluded due to a large number of missing values of response times (3 participants) or low picture-naming accuracy (i.e., < 60%, 2 participants). Therefore, the final sample consisted of 67 participants in total. They were all native Chinese speakers and started learning English at an average age of 8.19 years ( $SD = 2.42$  years, range: 3-15 years). Participants were randomly assigned to one of the three groups (i.e., left cerebellar stimulation, right cerebellar stimulation, & sham stimulation). They were matched on age, first language (L1) proficiency measured by the self-rating score, second language (L2) proficiency measured by the College English Test Band 4 (CET-4) and self-rating score, L2 age of acquisition, and cognitive control ability measured by the Simon score (for Simon task, see Liu et al. 2004; Kerns 2006). Participants' demographics were shown in Table 4.

#### **Table 4. Participants' demographics for the tDCS experiment**

Variables	Left cerebellar stimulation group	Right cerebellar stimulation group	Sham stimulation group	<i>F</i>	<i>p</i>
	<i>N</i> = 23 (18 females)	<i>N</i> = 22 (18 females)	<i>N</i> = 22 (10 females)		
Age	21.22 (1.83)	22.05 (2.15)	21.77 (1.97)	1.305	0.361
CET-4	533.26 (72.82)	536.55 (57.28)	534.09 (57.40)	0.016	0.984
L1 self- rating score	8.11 (1.15)	8.06 (1.27)	8.78 (1.04)	2.707	0.074
L2 self- rating score	5.73 (1.60)	5.61 (1.51)	6.02 (1.28)	0.452	0.638
L2 AoA	8.17 (2.23)	8.06 (1.27)	8.09 (2.22)	0.228	0.797
Simon score	27.65 (22.59)	19.17 (16.59)	28.89 (28.65)	1.155	0.322

**Note.** L2 AoA = L2 age of acquisition. Means (standard deviations) for the three groups of participants.

### ***Materials and procedure***

The procedure is illustrated in Figure 4. Before and after stimulation, participants completed the same picture naming task as the fMRI experiment. Specifically, all eighty images from the fMRI experiment were divided into two subsets, one for the pre-stimulation and the other for the post-stimulation session. These two subsets were well matched on visual complexity, familiarity, and naming agreement. They were also counterbalanced across participants. Additionally, participants also completed a digit naming task while receiving tDCS stimulation. During this task, digits of 0-9 were selected as the experimental stimuli. The same procedure as the picture naming task was used. The digit naming task included two sessions, each with 82 trials (2 filler trials, 20 L1 switch trials, 20 L1 non-switch trials, 20 L2 switch trials, and 20 L2 non-switch trials). The formal experiment lasted about 45 minutes.

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Insert Figure 4 Here  
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### ***tDCS protocol***

Cerebellar tDCS is a non-invasive and effective tool in stimulating cerebellar excitability (Grimaldi et al. 2014; Grimaldi et al. 2016). It has been adopted in modulating a variety of cognitive functions such as attention (Ferrucci et al. 2008), language (D'Mello et al. 2017), and emotion (Ferrucci et al. 2012). Anodal transcranial direct current stimulation was applied using the neuroConn DC stimulator MC (neuroCare Group) and the Soterix Medical HD-tDCS electrode system (Soterix Medical Inc.). In contrast to conventional tDCS which uses the large sponge electrodes, the Soterix Medical HD-tDCS electrode system was applied to target brain regions using high-definition gel-based electrodes. The anodal electrode was placed over the left/right posterolateral cerebellum (3 cm to the left/right of the inion, primarily lobules VI to VIII) using the HD electrode holder and the HD stimulation cap with the reference electrode on the ipsilateral buccinator. During anodal stimulation, the anodal current was ramped up to 2 mA over 30 s, applied for 14 min, and ramped down over 30 s. In sham conditions, the anodal current was ramped up over 30 s and immediately ramped down over 30 s at the beginning and at the end of the stimulation session (at the time point of 0 min and 14 min).

### **Results**

First, response times (RTs) for incorrect responses were excluded (14.77%). Then, RTs below 300 ms and above 2500 ms (0.92%), as well as 2.5 standard deviations shorter or longer than each participant's mean (1.88%) were discarded.

A 2 (Session: pre-stimulation/post-stimulation) \* 3 (Group: left cerebellar stimulation/right cerebellar stimulation/sham stimulation) ANOVA was performed on switch costs of response times and error rates, respectively. The analysis of response times showed a significant interaction between session and group ( $F(2, 64) = 4.494, p = 0.015, \eta_p^2 = 0.123$ ), whereas the main effect of session ( $F(1, 64) = 0.596, p = 0.443, \eta_p^2 = 0.009$ ) and group ( $F(2, 64) = 0.023, p = 0.977, \eta_p^2 = 0.001$ ) were not significant. Further simple effect analyses showed that the switch costs were significantly decreased after stimulation of the right cerebellum ( $p = 0.017$ ), whereas no significant difference was found in the left cerebellar stimulation group ( $p = 0.520$ ) and the sham stimulation group ( $p = 0.082$ ). In addition, the analysis of accuracy rates revealed no statistically significant results. Behavioral results of switch costs are presented in Table 5 and Figure 5A.

To further examine the stimulation effect, we extracted the data of the right cerebellar stimulation group and calculated the deduction of switch costs by subtracting the switch costs between the pre-stimulation and the post-stimulation sessions to represent the stimulation effect on language switching. A correlation analysis was performed to inspect the modulation of language proficiency on the stimulation effect in the right stimulation group. As shown in Figure 5B, the results showed a significant positive correlation between the CET-4 scores and the switch cost changes ( $r(21) = 0.459, p = 0.032$ ), suggesting that participants with higher L2 proficiency (higher CET-4 scores) showed better stimulation effect on language switching performance.

**Table 5.** Behavioral performance for the tDCS experiment.

Group	Session	Switch costs (RT, ms)	Switch costs (ER, %)
Left cerebellar stimulation	Pre-stimulation	59 (51.95)	2.01 (3.13)
	Post-stimulation	52 (38.25)	1.47 (2.76)

Right cerebellar stimulation	Pre-stimulation	70 (50.29)	1.08 (4.34)
	Post-stimulation	41 (42.28)	2.05 (3.17)
Sham stimulation	Pre-stimulation	47 (52.77)	1.65 (4.07)
	Post-stimulation	68 (44.07)	1.70 (3.12)

**Note.** RT: response time, ER: error rates. Means (standard deviations) for the three groups of participants in two sessions.

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 Insert Figure 5 Here  
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## Discussion

For the first time, the present study aimed to provide a comprehensive view of cerebellar activity during bilingual language control using both fMRI and tDCS. The results demonstrated that the bilateral posterolateral cerebellum were engaged in language control with different functions, and they formed a functional network with corresponding areas in the cerebral cortex.

### *Bilateral cerebellar activation and lateralization in language control*

Here, we found that the network for language control was organized in a symmetrical activation pattern in the cerebellum, i.e., bilateral lobules VI & VIII. These results confirmed the role of the cerebellum in language control, as revealed in some previous studies (Wang et al. 2007; Guo et al. 2011; de Bruin et al. 2014; Reverberi et al. 2018; Yuan et al. 2021). Different from previous research that has shown greater right-lateralization in the cerebellum involved in language processing (Price 2012), a symmetrical activation pattern was obtained

in the present study. One possible reason is that, unlike the verb generation task used in previous studies (e.g., Stoodley et al. 2012), the language switching task adopted in the present study is more likely to tap into language control in bilingual language production (e.g., Green 1998; Meuter and Allport 1999; Guo et al. 2011; Reverberi et al. 2015). For bilingual language control, previous studies have observed that the bilateral posterior cerebellum is activated (Price et al. 1999; Wang et al. 2007; Guo et al. 2011; de Bruin et al. 2014; De Baene et al. 2015; Fu et al. 2017; Reverberi et al. 2018; Wu et al. 2019). Such symmetrical activation pattern is also identical for the posterior cerebellum in processing other higher cognitive demands such as domain-general cognitive control (Stoodley and Schmahmann 2009). In addition, the bilateral posterior cerebellum is also detected to be functionally linked to the cerebral cortex to support language control. Both hemispheres of the cerebral cortex (including the bilateral dorsal anterior cingulate cortex/pre-supplementary motor area (dACC/pre-SMA), left prefrontal cortex, right inferior frontal gyrus, and bilateral inferior parietal lobe, thalamus, and the basal ganglia) has been observed activated during language control (Abutalebi and Green 2016); therefore, the connected bilateral posterior cerebellum may be activated through the cerebro-cerebellar connections.

However, we did observe lateralization in the cerebellum in the present study. The connectivity results showed that the connection strength from the lateral lobe to the medial lobe of the left lobule VI was negatively correlated with the switch cost. In contrast, the connection strength from the right lobule VI to its left counterpart and the connection strength from the medial lobe of the left lobule VI to the left lobule VIII were positively associated with the switch cost. One possible reason for such inverse associations is that the left and right cerebellum act differently during language control, a flexible cognitive process that can adapt to different contexts (Abutalebi and Green 2016). Furthermore, the neuro-behavioral causal relationship revealed by the tDCS showed a significant neuromodulation effect of the right



cerebellum, not the left cerebellum, on reducing language switch costs. To further probe this functional lateralization, some studies have discovered that the right cerebellar activation can help to predict the upcoming context during speech production and further modulate language production via cerebro-cerebellar connections (Lesage et al. 2012; Abutalebi and Green 2016). On the other hand, the left cerebellum participates more in executive functions, supporting language production by directing attention to current language contexts (Stoodley and Schmahmann 2009; Sulpizio et al. 2020). Therefore, we believe that both the left and the right activate for bilingual language control but may function differently.

### ***The cerebro-cerebellar network in language control***

In addition to local activity, the cerebellum's function also depends on cerebro-cerebellar circuits that support task performance (Ito 2006). Therefore, we modeled the cerebro-cerebellar network using effective connectivity analysis to discover how the cerebellum and the cerebral cortex would interact in bilingual language production. Accordingly, the current study found that the frontal, parietal, subcortical, and cerebellar areas interacted to build a network structurally containing intracerebral, intracerebellar, and cerebro-cerebellar connections, corresponding to a hierarchical processing pipeline of bilingual language control, which includes three key elements: conflict monitoring, interference suppression (from non-target language), and speech production in the target language (Abutalebi and Green 2007; Abutalebi and Green 2016).

Despite the symmetrical cerebellar activations found in univariate analyses, the intracerebellar language control network was centered on left lateral lobule VI. The lobule VI has been considered to be an overlap area of mossy fiber terminals, which support its role in complex cognition (Henschke and Pakan 2020). The current results showed that neural information flow originated from the left lobule VI to the left lobule VIII, right lobule VI and ended at the right lobule VIII. Previous studies have identified that the posterior cerebellum is

organized in a hierarchical manner for cognitive control (D'Mello et al. 2020). This hierarchical topography is consistent with previous neuroimaging results that the anterior part of the posterior lobe (lobules VI) is associated with higher cognitive processes (e.g., language and executive function), and the bilateral lobules VIII is associated with the motor function (Stoodley 2012). Language control requires the coordination of multiple demands from cognitive control (monitoring conflict and inhibiting the non-target language) and language production. Hence, the current connectivity pattern suggests that the lobules VI process initial cognitive control demands, and the lobules VIII receive control inputs for further signal processing.

For the cerebro-cerebellar network, unlike the hypothesis-driven network by Abutalebi and Green (2016), where the cerebellum is connected to the cerebral control network via basal ganglia, the current network pattern revealed an engagement of the lobule VI-dACC/pre-SMA connection, and the cerebellum connects to other frontal areas via the thalamus and the parietal cortex. These three pathways play different roles in bilingual language control. First, the bipolar left lobule VI-dACC/pre-SMA connection suggested that the dACC/pre-SMA sent conflicting information (Guo et al. 2011; Abutalebi et al. 2012; Abutalebi and Green 2016) to the left lobule VI to support the production of the target language and that the bilateral lobules VI also supported conflict detection based on their attentional functions (Stoodley et al. 2012). Second, the left lateral lobule VI also received information from the left inferior parietal lobe. This connection indicates that the left inferior parietal lobe is involved in attentional maintaining of current language representations for the cerebellum to perform future control processing (Abutalebi and Green 2008). Finally, the left medial lobule VI sent information to the left thalamus, which transferred cerebellar signals back to the basal ganglia (caudate) and the cerebral cortex. This difference reconciles that the thalamus is a core neural apparatus that receives afferent connections from the posterior cerebellum and provides a link to the basal

ganglia, which transfers execution signals to the frontal cortex (Seo et al. 2018). Early studies have suggested that cognition is mediated mainly by contralateral cerebro-cerebellar pathways and often disregarded the importance of ipsilateral pathways (Salmi et al. 2010; Buckner et al. 2011). However, recent anatomical studies have discovered that ipsilateral white matter tracks can be identified (Karavasilis et al. 2019), and all cerebellar lobules receive neural projections from both the left and right hemispheres of the cerebral cortex (Henschke and Pakan 2020). The function of these ipsilateral connections is suggested to be involved in language and other complex cognitive processes (Van Overwalle et al. 2020). The current connectivity pattern was most ipsilateral, and the cerebellum projected to contralateral frontal areas through the left thalamus. The current ipsilateral connection may suggest its importance in transferring conflict (or attentional) information for instant monitoring (or language maintaining) between the left lobule VI and the dACC/pre-SMA (or the left inferior parietal lobe) during bilingual language control because this connection is more direct compared with the contralateral connections through the left thalamus. However, the role of the ipsilateral cerebro-cerebellar connection in processing complex cognitive demands requires further investigation.

Finally, for the intracerebral network, the current study revealed a dACC/pre-SMA-centered network with connections among frontal, parietal, and subcortical areas. This current cerebral network pattern was also consistent with our previous studies, which supported conflict monitoring and cognitive control in bilingual language production (For a detailed discussion, see Wu et al. 2019; Yuan et al. 2021).

### ***The functional plasticity of the cerebellum***

Experiment 2 showed a significant stimulation effect of the right cerebellum on bilingual language control. Regarding the neural plasticity of the cerebellum in bilingual language control, one of our previous studies discovered that both language switching costs and the activity of the ACC associated with conflict monitoring were reduced by short-term language

switching training (Kang et al. 2017). More importantly, behavioral improvement and the reduction of neural activity were positively correlated to each other, suggesting that language switching performance is modulated by the activity of the ACC. According to the aforementioned effective connectivity map, the dACC/pre-SMA, one of the network cores, directly connects to the right cerebellum. Therefore, it is possible that stimulating the right cerebellum induced a decrease in language switching costs through the link to the ACC. In fact, it has been shown that the stimulation over the right posterolateral cerebellum can significantly improve phonemic fluency in language production by enhancing the functional connectivity between the right cerebellum and the cerebral cortex (Turkeltaub et al. 2016). This type of neural plasticity is also modulated by other factors such as language proficiency (Chen et al. 2020). Indeed, the current correlation analysis also illustrated that a bilingual with higher L2 proficiency experienced a better stimulation effect (i.e., a more considerable switch cost reduction). The result confirmed that bilinguals with higher L2 proficiency tended to exhibit better brain plasticity of instant focal stimulation. The result is also consistent with the previous finding that language proficiency influences bilingual language control (Costa and Santesteban 2004; Costa et al. 2006; Abutalebi, Della Rosa, Ding, et al. 2013). Given that highly proficient bilinguals are often linked with enhanced language control abilities (Green and Abutalebi 2013), the language control network of these individuals may be more easily stimulated to produce a more efficient neuromodulation effect compared with less proficient bilinguals. Moreover, the present results also suggest that bilinguals' language proficiency can modulate the neural activity and plasticity of the cerebellum. For bilinguals, anatomical studies have illustrated that the left cerebellum is strengthened (in gray matter density and cortical thickness) after learning and using their second language (Pliatsikas et al. 2014). Also, Rossi et al. (2021) observed left cerebellar activation during bilinguals' comprehension of codeswitched sentences. These results suggest that bilingual language production and comprehension are likely to

request a structural or functional change in the cerebellum due to a higher demand for executive control. In return, changes in cerebellar activities and cerebro-cerebellar connections can be characterized as neural correlates that can predict different types of bilingual language experience (Grundy et al. 2017; DeLuca et al. 2019).

In contrast, stimulation of the left cerebellum did not yield any significant modulation effect. According to the brain network delineated by our fMRI experiment, the left posterolateral cerebellum participates in a more dispersed network with more connections to the frontal and parietal areas associated with domain-general cognitive control. Furthermore, several recent brain stimulation studies (Tong et al. 2020; Ware et al. 2021) failed to obtain any significant stimulation effect in behavioral performance when stimulating the dorsolateral prefrontal cortex. Thus, it is reasonable to speculate that it might be difficult to observe behavioral outcomes simply by facilitating neural activity the left cerebellum. Instead, it might be possible to get significant effects by perturbing the left cerebellum or with patients of specific lesions in either the left cerebellum or the right cerebellum. Future studies should explore this possibility to further reveal the cerebellum's role in bilingual language control.

To a step further, the cerebellum functions in human cognition via cerebro-cerebellar circuits not only in the language function but also in almost all higher cognitive functions. Previous studies have proposed that the cerebellum plays a simple role in local neural computations, and its cognitive functions can be defined by its efferent and afferent connections (Ramnani 2006; Eccles 2013). In line with this, several studies have discovered that different cerebellum subregions functionally and structurally connect to different areas in the cerebral cortex (Krienen and Buckner 2009; Buckner et al. 2011; Ji et al. 2019). These coupled areas co-activate in cognitive tasks (Stoodley et al. 2010, 2012) and function as a topographically organized network (Kellermann et al. 2012). Taken together, the present study directly illustrated that the posterolateral cerebellum is functionally organized asymmetrically

and appears to have a homotopical mapping of the cerebral cortex through the cerebro-cerebellar network.

### ***Limitations***

Also, we would like to point out some limitations of the current study. First, we explained that the left cerebellum was more engaged in the control network, and the right cerebellum was more involved in language production. However, the current results could not address this question directly. Future studies may investigate this issue using TMS (transcranial magnetic stimulation) to perturb the left and the right cerebellum activity or with patients of specific lesions in either the left cerebellum or the right cerebellum. Second, only behavioral responses were measured in Experiment 2. Therefore, the brain activity and connectivity changes due to brain stimulation and its relationships with language switching outcomes cannot be modeled in the current study. Future studies may consider combining brain stimulation and neuroimaging approaches (e.g., Jung and Lambon Ralph 2016) to directly model short-term neural plasticity in response to focal stimulation.

### **Conclusion**

To sum up, using fMRI and tDCS, respectively, our study revealed asymmetrical cerebellar participation in language control. Such asymmetrical patterns revealed distinct roles for the left and right cerebellum in bilingual language production. Furthermore, the current study also has implications for understanding the asymmetrical and discrete functional organization of the cerebellum in human cognitive processes.

## **Acknowledgments**

We thank Shunsen Huang for his help with the specification curve analysis. We also thank Alex Titus and Dr. Eric Pelzl for proofreading the manuscript.

## **Funding**

The study was supported by the National Natural Science Foundation of China (31871097), the National Key Basic Research Program of China (2014CB846102), the Interdisciplinary Research Funds of Beijing Normal University, and the Fundamental Research Funds for the Central Universities (2017XTCX04).

## **Notes**

Conflict of Interest: None declared.

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## Tables

**Table 1.** Behavioral measures of the Experiment 1

Behavioral measures	Gender	Age	CET-4	L1 self-rating score	L2 self-rating score	L2 AoA
<b>Value</b>	25 females	22.5 (2.1)	540 (44)	7.93 (1.15)	5.61 (1.28)	9.45 (2.45)

**Note.** L2 AoA = L2 age of acquisition. Means (standard deviations) of participants.

**Table 2.** Cerebellar activation of language control (contrast: switch > non-switch)

Region	Cluster size	MNI coordinates (x, y, z)			<i>t</i> value
L.lobule VI (lateral)	332	-36	-50	-29	7.24
L.lobule VI (medial)	106	-4	-66	-15	5.74
L.lobule VIII	406	-20	-62	-51	6.93
R.lobule VI	760	28	-68	-19	7.38
R.lobule VIII	100	30	-58	-53	7.11

**Note.** L = left, R = right, lateral/medial = lateral/medial surface of the hemisphere.

Uncorrected  $p < 0.001$  at voxel level and GRF-FWE corrected  $p < 0.05$  at cluster level.

**Table 3.** Bootstrapped results of the specification curve analysis

Neural indicators (Connection strengths)	The median standardized regression coefficients		Number of significant positive associations		Number of significant negative associations	
	$\beta$	<i>p</i>	<i>N</i>	<i>p</i>	<i>N</i>	<i>p</i>
L.lobule VI (med.) → L.lobule VIII	142.3	< 0.001	6	0.003	0	1

R.lobule VI → L.lobule VI (med.)	123.67	< 0.001	8	< 0.001	0	1
L.lobule VI (lat.) → L.lobule VI (med.)	-108.52	< 0.001	0	1	8	< 0.001
L.Thal → R.Thal	-191.2	< 0.001	0	1	6	< 0.001

Note:  $N$  = the number of specification models in each specification curve analysis which the positive/negative regression coefficient is statistically significant at  $p < 0.05$ . The total number of specifications for each indicator is 8. The bootstrapping was performed 1000 times. Brain nodes: L.Thal = left thalamus, R.Thal = right thalamus, L.lobule VI (lat./med.) = left lobule VI (lateral/medial), L.lobule VIII = left lobule VIII, R.lobule VI = right lobule VI. Arrows represent the direction of each connection.

**Table 4. Participants' demographics for the tDCS experiment**

Variables	Left cerebellar stimulation group	Right cerebellar stimulation group	Sham stimulation group	$F$	$p$
	$N = 23$ (18 females)	$N = 22$ (18 females)	$N = 22$ (10 females)		
Age	21.22 (1.83)	22.05 (2.15)	21.77 (1.97)	1.305	0.361
CET-4	533.26 (72.82)	536.55 (57.28)	534.09 (57.40)	0.016	0.984
L1 self-rating score	8.11 (1.15)	8.06 (1.27)	8.78 (1.04)	2.707	0.074
L2 self-rating score	5.73 (1.60)	5.61 (1.51)	6.02 (1.28)	0.452	0.638
L2 AoA	8.17 (2.23)	8.06 (1.27)	8.09 (2.22)	0.228	0.797
Simon score	27.65 (22.59)	19.17 (16.59)	28.89 (28.65)	1.155	0.322

**Note.** L2 AoA = L2 age of acquisition. Means (standard deviations) for the three groups of participants.

**Table 5.** Behavioral performance for the tDCS experiment.

Group	Session	Switch costs (RT, ms)	Switch costs (ER, %)
Left cerebellar stimulation	Pre-stimulation	59 (51.95)	2.01 (3.13)
	Post-stimulation	52 (38.25)	1.47 (2.76)
Right cerebellar stimulation	Pre-stimulation	70 (50.29)	1.08 (4.34)
	Post-stimulation	41 (42.28)	2.05 (3.17)
Sham stimulation	Pre-stimulation	47 (52.77)	1.65 (4.07)
	Post-stimulation	68 (44.07)	1.70 (3.12)

**Note.** RT: response time, ER: error rates. Means (standard deviations) for the three groups of participants in two sessions.

## Captions to figures

**Figure 1. Cerebellar activation results.** Cerebellar activation results were presented as a  $T$ -map with a threshold of uncorrected  $p < 0.001$  at the voxel level and GRF-FWE corrected  $p < 0.05$  at the cluster level.

**Figure 2. The Cerebro-cerebellar networks of bilingual language control.** The location of each node was defined by the MNI coordinates of the Human Brainnetome Atlas (Cerebral nodes, Fan et al. 2016) and the cerebellar activation results (cerebellar nodes). The intracerebral, intracerebellar, and cerebro-cerebellar connections were marked in blue, green, and red, respectively. The cores were marked in red, and the cerebral and cerebellar nodes were marked in blue and green, respectively. dACC/pre-SMA = dorsal anterior cingulate cortex/pre-supplementary motor cortex, L.MFG = left medial frontal gyrus, R.IFG = right inferior frontal gyrus, L.IPL = left inferior parietal lobe, L.CN = left caudate nucleus, L.Thal = left thalamus, R.Thal = right thalamus, L.lobule VI (lat./med.) = left lobule VI (lateral/medial), L.lobule VIII = left lobule VIII, R.lobule VI = right lobule VI, R.lobule VIII = right lobule VIII.

**Figure 3. Specification curve.** **A**, the specification curve for each predictor (connection strength) and the outcome (switch cost). The standardized regression coefficient was ordered by effect size. The red/blue dot indicates a significant negative/positive regression coefficient ( $p < 0.05$ ) with the vertical line showing the 95% confidence interval around it. **B**, each specification model with the selection of indicators and control variables. The red/blue vertical lines show the significant negative/positive model specifications corresponding to the dots in the top panel. predictors = predictive variables, outcome = outcome variable, controls = control variables. Brain nodes: dACC/pre-SMA = dorsal anterior cingulate cortex/pre-supplementary motor cortex, L.MFG = left medial frontal gyrus, R.IFG = right inferior frontal gyrus, L.IPL = left inferior parietal lobe, L.CN = left caudate nucleus, L.Thal = left thalamus, R.Thal = right

thalamus, L.lobule VI (lat./med.) = left lobule VI (lateral/medial), L.lobule VIII = left lobule VIII, R.lobule VI = right lobule VI, R.lobule VIII = right lobule VIII.

**Figure 4. Experiment procedure (tDCS experiment).** Participants completed a picture-naming task before and after the tDCS stimulation and a digit naming task during the tDCS stimulation. The red electrode represents the anode, whereas the blue electrode represents the cathode (reference electrode). The brain icon is adapted from <http://pngimg.com/image/86560>, under Creative Commons 4.0 BY-NC.

**Figure 5. Behavioral results for the tDCS experiment.** *A*, switch costs of response time were significantly decreased by the right-cerebellar stimulation (Left/Right stimulation = Left/Right cerebellar stimulation group). *B*, correlation analysis showed a significant positive correlation between L2 proficiency (measured by CET-4 scores) and the switch cost change.