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The effect of bilingualism on the functional neuroplasticity of the cerebellum

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Abstract

Previous studies revealed structural differences in cerebellar regions between monolinguals and bilinguals. However, the effect of bilingual experiences on cerebellar functional neuroplasticity remains unclear. Using resting-state functional magnetic resonance imaging (fMRI) data, we compared cerebellar functional connectivity (FC) between monolinguals and bilinguals, and then examined how age of second language acquisition (AoA-L2), immersion of L2 (Immersion-L2), proficiency level of L2 (PL-L2) and usage of L2 (Usage-L2) influence cerebellar FC in bilinguals. We found monolinguals exhibited increased FC between lobules VI, VIIIa and superior temporal gyrus. Increased AoA-L2 was related to decreased cerebello-cortical FC involving lobules VI, CrusI and precentral gyrus. Increased Immersion-L2 was associated with decreased cerebello-orbitofrontal FC. Higher PL-L2 corresponded to stronger cerebellar FC with posterior cingulate gyrus. Bilinguals who used L2 more frequently at home exhibited decreased cerebellar FC, while increased social Usage-L2 was associated with increased FC. These findings highlight bilingualism's impact on cerebellar functional neuroplasticity, shaped by different bilingual experiences.

Highlights

- Monolinguals exhibit significantly higher cerebello-cortical FC than bilinguals.
- Acquiring L2 late is associated with increased cerebello-caudate FC.
- Increased Immersion-L2 is linked to decreased cerebellar FC.
- Using L2 at home more frequently exhibits decreased cerebello-cortical FC.
- Increased Usage-L2 in social settings is related to higher cerebello-cortical FC.

1. Introduction

The cerebellum, traditionally associated with motor functions, has been increasingly focused on its involvement in language processes (LeBel & D'Mello, 2023; Turker et al., 2023; Yuan et al., 2023). The neural activation of the cerebellum was observed during different language tasks in bilinguals (Sulpizio et al., 2020b; Yuan et al., 2021). In particular, the cerebellum plays a role in phonological and grammatical learning, as well as in language control mechanisms (Abutalebi & Green, 2016; De Smet et al., 2013; Pliatsikas et al., 2014). According to the Adaptive Control Hypothesis (ACH) (Green & Abutalebi, 2013), the cerebellum is thought to be involved in the adaptation of language control in bilinguals to effectively manage the demands of inhibiting non-target language in different conversational contexts. It seems that there has been a consensus on the role of the cerebellum relating to increased efficiency in language control (DeLuca et al., 2019, 2020b; Green & Abutalebi, 2013; Pliatsikas, 2020). Indeed, compared to monolinguals, bilinguals require additional demand for language control to ensure effective communication. This may induce structural alteration of relevant brain control regions, including the cerebellum, in bilinguals, which reflects the neuroplasticity of learning and using a second language (L2) with a longitudinal effect (Pliatsikas, 2020).

Evidence from neuroimaging studies has shown the structural difference in the cerebellum between monolinguals and bilinguals (Danylkiv & Krafnick, 2020; Jin et al., 2023; Schug et al., 2022). For example, Jin et al. (2023) found that Cantonese-Mandarin bilinguals showed larger gray matter volume (GMV) in the posterior lobe (bilateral lobules VIIIa, VIIIb and IX), the flocculonodular lobe (right lobule X), and the vermis (VIIIb and IX) compared to Mandarin monolinguals. The increased GMV in the cerebellum can be observed in different stages of learning L2, which may reflect the structural neuroplasticity to adapt in response to increased demands of language processing in bilinguals (Pliatsikas, 2020). In addition, a recent study investigated structural differences in the cerebellum between bilingual and monolingual children (Nguyen et al., 2024). The results showed that bilingual children had smaller cerebellar volumes

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than monolingual children, and cerebellar volume was positively associated with English vocabulary in both groups. The finding of smaller cerebellar volume in bilingual children compared to their monolingual peers may be due to a delayed peak in cerebellar development caused by increased exposure to multiple languages.

It seems that the structural change of the cerebellum was also potentially related to bilingual experiences, such as the age of L2 acquisition (AoA-L2), the immersion of L2 (Immersion-L2), the proficiency level of L2 (PL-L2) and the usage of L2 (Usage-L2) (DeLuca et al., 2019, 2020b; Pliatsikas, 2020; Wang et al., 2020). Previous studies have shown that increased Immersion-L2 led to the cerebellum being more responsive to experience-based restructuring, suggesting that the amount of exposure to L2 influences the structural neuroplasticity of the cerebellum in proficient bilinguals (DeLuca et al., 2019). According to the Dynamic Restructuring Model (DRM), bilingual experiences induce structural alterations in the cerebellum that evolve across three distinct stages (Pliatsikas, 2020). In the initial stage, exposure to L2 leads to an expansion of cerebellar GMV due to the increased cognitive demands associated with language control and selection between first language (L1) and L2. During the consolidation stage, cortical expansions undergo renormalization, optimizing neural efficiency by eliminating redundant local connections. However, cerebellar GMV continues to increase, as bilinguals sustain the demands for language control and selection. In the final stage, peak efficiency may be achieved, with cerebellar structural adaptations potentially facilitating optimized bilingual language control and integration, thereby supporting more automatic and fluent L2 processing. Based on the Unifying the Bilingual Experience Trajectories (UBET) framework, structural alterations in the cerebellum resulting from prolonged bilingual experience reflect a shift toward greater efficiency in executive control (DeLuca et al., 2020b). As bilinguals become more proficient in managing multiple languages, the cerebellum not only continues to support the coordination of motor functions essential for speech production but also plays a critical role in the cognitive processes underlying language control. However, it should be noted that limited immersion in an L2 environment, varying proficiency levels, and differences in daily language-switching demands may contribute to the absence of detectable cerebellar adaptations. This highlights the importance of considering the interaction between bilingual experiences and environmental context when interpreting neuroanatomical findings (DeLuca et al., 2024). While an increasing number of studies have examined the effects of bilingualism on structural alterations in the cerebellum, the functional neuroplasticity of the cerebellum modulated by bilingualism is not completely clear. Investigating differences in the intrinsic neural activity patterns of the cerebellum between monolinguals and bilinguals may reveal how distinct L1 and L2 experiences influence the functional organization of the cerebellum. Also, this may improve our understanding of the neural mechanisms through which the cerebellum interacts with cortical and subcortical regions to support bilingual language control.

Using functional magnetic resonance imaging (fMRI), previous studies have investigated the effect of bilingualism on resting-state functional connectivity (FC) of the cerebellum in bilinguals (Berken et al., 2016; Jin et al., 2023). In Jin et al. (2023)'s study, they found that significantly increased FC between the right inferior posterior lobe of the cerebellar and the orbital part of the left inferior frontal gyrus (IFG) in bilinguals compared to monolinguals. Also, this functional neuroplasticity was positively correlated with the response time of L1 alphanumeric rapid automatized naming. These findings suggested that bilingualism influences the functional alteration of the cerebello-cortical circuit, particularly in the processing of the L1. In addition, Berken et al. (2016) applied a seed-based analysis to examine the effect of AoA-L2 on resting-state FC. They observed stronger FC between the bilateral posterior cerebellum and IFG in simultaneous bilinguals compared to sequential bilinguals. This result suggested that early exposure to L2 induces functional neural plasticity of language-related cortical and cerebellar regions, which may potentially enhance language processing ability and cognitive function.

However, there is still a lack of studies to systemically investigate the functional neuroplasticity of the posterior cerebellum that relates to different bilingual experiences, such as AoA-L2, Immersion-L2, PL-L2 and Usage-L2. The posterior cerebellum is anatomically composed of lobules VI, CrusI, CrusII, VIIIb, VIIIa, VIIIb and IX. Recent studies revealed that these cerebellar regions were associated with relevant language processes (D'Mello et al., 2020; Li et al., 2021; Yuan et al., 2023). For example, the activation of the bilateral cerebellar VIIIa was observed during sentence reading (D'Mello et al., 2020), and the activation of left lobule VII extended to lobule VIII negatively correlated with individual reading ability (Li et al., 2021). Whether bilingual experiences influence the FC of the posterior cerebellum remains unclear. Revealing the effects of bilingual experiences on the intrinsic connectivity patterns of the cerebellum may contribute to a more comprehensive understanding of how different experience-based factors shape its functional organization in bilinguals.

In this study, we aimed to investigate the effect of bilingualism on functional neuroplasticity of the cerebellum. We first examined the difference in whole-brain FC of the cerebellum between bilinguals and monolinguals. Then we constructed the cerebellar network based on intra-cerebellar FC and used the graph theory to analyze the topological properties of the cerebellar network. Graph theory has been widely used to characterize the topological properties of language functional networks in previous studies (Liu et al., 2017, 2021; Sulpizio et al., 2020a). The clustering coefficient (C_w), characteristic path length (L_w), global efficiency (E_{glob}) and local efficiency (E_{loc}) were used to describe the topological properties of the cerebellar network. The C_w reflects the local connectivity within the cerebellum, indicating the strength of connections among neighboring nodes. The L_w quantifies the average number of steps required for information transfer across the cerebellar network. The E_{glob} and E_{loc} measure the efficiency of information transfer between different nodes in the entire cerebellar network and within localized regions, respectively. These parameters capture both local and global network characteristics, providing a comprehensive evaluation of how bilingual experiences influence cerebellar neural organization. Given that the cerebellum plays an important role in bilingual language control and motor functions, analyzing its topological properties may help us understand its functional adaptations associated with bilingualism. Both FC and topological properties were used to reflect functional neuroplasticity of the cerebellum induced by bilingualism. Next, we focused on the effect of four bilingual experience-based factors, the AoA-L2, the Immersion-L2, the PL-L2 and the Usage-L2, on FC between each subregion of the posterior cerebellum and whole-brain regions. For the Usage-L2, we investigated its role in shaping cerebellar FC in different contexts, specifically at home and in social settings. This distinction is theoretically rooted in the ACH, which proposes that structural and functional adaptations of bilinguals are shaped by the specific context of Usage-L2 (Green & Abutalebi, 2013). Lower scores on Usage-L2 at home would suggest that the home remains primarily an L1 domain, while broader social contexts serve as a (potentially) L2-dominant environment. In contrast, higher Usage-L2 in social settings may better capture a dense code-switching context. Given that Usage-L2 in different contexts may engage distinct control mechanisms, distinguishing between these two aspects of bilingual experience allows us to better isolate their potential effects on cerebellar FC and bilingualism-induced neuroplasticity. We used a seed-based analysis to calculate the cerebello-cortical and cerebello-subcortical FC, and applied a multiple regression analysis to investigate how AoA-L2, Immersion-L2, PL-L2 and Usage-L2 (at home and in social settings) influence cerebellar FC in bilinguals. Most previous studies only examined a single bilingual experience-based factor influencing structural or functional neuroplasticity (Berken et al., 2016; Liu et al., 2021; Mouthon et al., 2020; Tu et al., 2015; Zhao et al., 2023). To better reveal the synthetical impact of bilingual experiences on functional neuroplasticity of the posterior cerebellum, another two factors, L1 spoken and the exposure to a third (or more) language, were included in the multiple regression model. In addition, previous studies have typically characterized bilingualism using qualitative classifications, categorizing individuals into discrete groups such as early versus late bilinguals based on AoA-L2 (Berken et al., 2016; Liu et al., 2017; Sheng et al., 2023) or high- versus low-proficient bilinguals based on PL-L2 (Mouthon et al., 2020). However, the criteria for defining early and late bilinguals or high- and low-proficient bilinguals vary across studies, making it difficult to establish clear boundaries or critical periods for classification. This categorical approach may contribute to inconsistencies in the literature, as it overlooks the continuous and dynamic nature of bilingual experiences. To better capture the neural adaptations associated with bilingualism, the present study employed continuous measures of bilingual experiences, enabling a more precise and nuanced analysis. This methodological shift aligns with an increasing number of studies that have adopted continuous variables to examine the effects of bilingual experiences on functional and structural neuroplasticity (DeLuca et al., 2019; 2020a; Korenar et al., 2023a; Sulpizio et al., 2020a).

2. Methods

2.1. Subjects

We accessed 52 monolingual subjects (28 females, age: mean ± SD, 22.85 ± 4.66 yrs, range: 18–40) from “The Reading Brain Project L1 Adults” dataset (https://openneuro.org/datasets/ds003974/versions/3.0.0) (Dataset1) (Follmer et al., 2018; Li & Clariana, 2019) and 56 bilingual subjects (30 females, age: mean ± SD, 25.14 ± 4.74 yrs, range: 19–38) from “The Reading Brain Project L2 Adults” dataset (https://openneuro.org/datasets/ds003988/versions/1.0.0) (Dataset2) (Table 1). Monolingual subjects (Dataset1) were recruited from Pennsylvania State Hershey Medical Center; they are all native English speakers. Bilingual subjects (Dataset2) are native speakers of Mandarin Chinese, learning English as L2. In order to investigate whether bilingual experiences induced functional neuroplasticity of the cerebellum, we future accessed 64 bilingual subjects (49 females, age: mean ± SD, 31.91 ± 7.60 yrs, range: 18–52) from the “Bilingualism and the Brain” dataset (https://openneuro.org/datasets/ds001796/versions/1.3.0) (DeLuca et al., 2019) (Dataset3) (Table 1). Compared to Dataset2, Dataset3 provides more detailed information on bilingual experiences. Specifically, Dataset3 includes measures such as AoA-L2, Immersion-L2, PL-L2, Usage-L2, L1 spoken and exposure to a third (or more) language, which are crucial for examining how different bilingual experiences influence functional neuroplasticity of the cerebellum. In this dataset, bilingual subjects spoke diverse L1, but they all spoke English as their L2, with varying AoA-L2 (mean ± SD, 8.31 ± 4.65 years old, range: 0–22 years old). The majority of them were born in other countries and moved to the United Kingdom at different ages. At the time of the experiment, they were all living in the United Kingdom. The Immersion-L2 was estimated for each subject (mean ± SD, 71.94 ± 73.84 months, range: 0.26–383.85) to reflect how long they had continuously lived in the United Kingdom before the experiment. All bilingual subjects self-reported as proficient and frequent users of English. The PL-L2 was assessed by using the Oxford Quick Placement Test (QPT) for each subject. The results showed that the QPT score was 53.03 ± 6.55 (63 subjects, mean ± SD, range 31–60), suggesting that they were high-intermediate to high-proficiency speakers of English. Meanwhile, they completed the Language and Social Background Questionnaire (LSBQ) to estimate the usage of known language from early childhood to the present day in a range of settings. According to the results of LSBQ, the detailed extents of Usage-L2 at home and in social settings were further derived as weighted aggregate scores by using a factor score calculator. Bilingual subjects with a higher score reflect more usage of the L2, while a lower score indicates more usage of the L1 in these two different settings. The results showed a mean score of 2.55 (SD: 5.09, range: −7.15–16.70) for Usage-L2 at home and a mean score of 51.66 for Usage-L2 in social settings (SD: 11.38, range: 10.77–74.53). In addition, several bilingual subjects (n = 33) reported knowledge of additional languages (L3) beyond their native language and English. The L3 experience was calculated as a percentage of engagement. This was based on responses to four questions related to reading, writing, speaking and listening for each language. The average language exposure of L3 is 0.13 (SD: 0.26, range: 0–1.5). This potential effect of the L3 experience was included as a nuisance covariate in subsequent analysis. For the educational level, all subjects reported they hold at least a post-secondary or diploma degree. More detail information about the

Table 1. Descriptive statistics of demographic and linguistic measures

	Mean (SD)	Range
Dataset1		
Age	22.94 (4.65)	18–40
Gender (M/F)	26/25	–
Dataset2		
Age	25.14 (4.74)	19–38
Gender(M/F)	26/30	–
Dataset3		
Age (years old)	31.9 (7.60)	18–52
Gender (M/F)	15/49	–
AoA-L2 (English, years)	8.31 (4.65)	0–22
PL-L2 (QPT score)	53.03 (6.55)	31–60
Immersion-L2	71.94 (73.84)	0.26–383.85
Usage-L2 at home	2.55 (5.09)	−7.15–16.7
Usage-L2 in settings	51.66 (11.38)	10.77–74.53

Note: Mean, standard deviation (SD), and range for each measure are listed.

subjects can be found in Supplementary Table S1 and the "Methods, Participants and Materials" section of DeLuca et al. (2019)'s study.

2.2. MRI data acquisition

All MRI data from Dataset1 and Dataset2 were acquired on a 3 T Siemens MAGNETOM Prisma Fit scanner with a 64-channel phased array coil. The resting-state fMRI data were obtained using a single-shot gradient-echo echo-planner imaging (GE-EPI) sequence with the following parameters: repetition time (TR) = 2000 ms, echo time (TE) = 30 ms, flip angle (FA) = 90°, field of view (FoV) = 240 mm × 240 mm, slice thickness = 4 mm without gap, 34 interleaved axial slices with A/P phase encoding direction and a total of 150 time points acquired in 5 mins. During the resting-state fMRI scanning, each subject was requested to look at the cross on the screen, but not think about anything. In addition, high-resolution brain structural images for each subject were acquired by using an MPRAGE sequence (TR/TE = 1,540;ms/2.34 ms, FA = 9°, FoV = 256 × 256 mm, slice thickness = 1.0 mm, voxel size = 1.0 × 1.0 × 1.0 mm^3 and 176 sagittal slices covering the whole brain).

Similar to Dataset1 and Dataset2, the MRI data from Dataset3 were acquired on a 3 T Siemens MAGNETOM Prisma Fit scanner but with a 32-channel head matrix coil. The functional images were obtained using a single-shot GE-EPI sequence. Specific parameters of the sequence were as follows: TR = 1,500 ms, TE = 30 ms, FA = 66°, FoV = 192 mm × 192 mm, voxel size 2.1 × 2.1 × 2.0 mm^3, 68 transversal slices with 2.0 mm slice thickness and 300 volumes acquired in 7.5 mins. Also, the field maps (gradient echo images, TE: 7.38 and 4.92 ms) were acquired for each subject. Using an MPRAGE sequence, the high-resolution brain structural images for each subject were obtained (TR/TE = 2,400 ms/2.41 ms, FA = 8°, FoV = 250 × 250 mm, slice thickness = 0.7 mm, voxel size = 0.7 × 0.7 × 0.7 mm^3 and 256 sagittal slices covering the whole brain). Each subject was asked to lie quietly and open his or her eyes but not to think about anything during the whole scanning.

2.3. MRI data preprocessing

Functional imaging data were preprocessed in SPM 12 (http://www.fil.ion.ucl.ac.uk/spm) and DPABI (version 7.0, http://rfmri.org/dpabi). The preprocessing was consistent across three datasets. The first 10 volumes were discarded to allow the MRI signal to reach a steady state. Then, we performed slice timing for the remaining volumes and realigned them to the first volume for head-motion correction. The mean framewise displacement (FD) was estimated to check the head-motion information for each subject. Subsequently, we regressed out the nuisance covariates including the head-motion profiles derived from the Friston 24-parameter model, white matter signal and cerebrospinal fluid signal, and performed the signal linear detrending within each voxel in the whole brain. In the next step, all function images were spatially normalized to the standard MNI template by using DARTEL normalization and then resampled to a voxel size of 3 × 3 × 3 mm with a kernel of full-width at half maximum (FWHM) of 8 mm. Finally, the data were band-pass filtered (0.01–0.08 Hz).

2.4. Definition of regions of interest (ROIs)

We defined regions of interest (ROIs) for the cerebellum from the probabilistic MR Atlas of the human cerebellum (Diedrichsen et al., 2009). This cerebellar atlas was integrally extracted from the Cerebellar toolbox (SUIT, https://www.diedrichsenlab.org/imaging/suit.htm). We selected cerebellar ROIs from the probabilistic MR atlas of the human cerebellum due to its provision of an unbiased and anatomically detailed reference for assigning lobular labels. This approach minimizes localization errors compared to single-subject anatomical references. The atlas quantifies the certainty of anatomical assignments, thereby enhancing the accuracy in evaluating and integrating empirical evidence. Furthermore, it facilitates ROI analyses through maximum-probability maps, which enable efficient extraction of functional and structural data while supporting hypothesis-driven investigations without necessitating extensive multiple comparison corrections. Importantly, the atlas has been validated for its superior alignment and normalization of cerebellar structures, as cerebellum-specific normalization methods outperform whole-brain approaches. These advantages render the atlas a robust tool for ensuring anatomical accuracy and methodological consistency in cerebellar research. In total, we selected 28 cerebellar subregions, including 10 cerebellar lobules for each hemisphere (lobules I-IV, V, VI, Crus I, Crus II, VIIb, VIIIa, VIIIb, IX and X) and 8 vermis (vermis VI, Crus I, Crus II, VIIb, VIIIa, VIIIb, IX and X). All cerebellar subregions were resampled to a voxel size of 3 mm^3 for subsequent analysis. The cortical ROIs were extracted from the Automated Anatomical Labelling (AAL, version 3) atlas (Rolls et al., 2020). The AAL atlas includes 86 cortical regions in two hemispheres. The subcortical ROIs were extracted from the Melbourne Subcortex Atlas (Tian et al., 2020). In total, based on the second hierarchical scale of this atlas, 32 subcortical ROIs including the anterior and posterior hippocampus (aHIP and pHIP), globus pallidus (aGP and pGP), caudate (aCAU and pCAU), putamen (aPUT and pPUT), two subdivisions of nucleus accumbens (NA-shell and NA-core), the lateral and medial amygdala (lAMY and mAMY) and dorso- and ventroanterior and dorso- and ventroposterior thalamus (daTHA, vaTHA, dpTHA and vpTHA) for both hemispheres were selected. In contrast to previous studies that focused on specific brain regions involved in bilingual processing and control, we adopted an exploratory, data-driven approach by including all cortical and subcortical regions to calculate cerebellar FC. Rather than restricting our investigation to predefined regions based on existing bilingual models, we adopted an exploratory, data-driven approach that allowed us to systematically examine how different language experiences influence cerebello-cortical and cerebello-subcortical FC. Additionally, it facilitates the identification of novel regions functionally connected with the cerebellum in relation to bilingual experiences, complementing prior research that has primarily focused on predefined regions. Supplementary Figure S1 shows different anatomical orientations and slices of the cerebellar, cortical and subcortical regions. Supplementary Table S2 lists all cortical and subcortical regions with corresponding abbreviations.

2.5. Whole-brain FC map of the cerebellar subregions

To investigate differences in cerebellar FC between bilinguals and monolinguals, we calculated the whole-brain FC map of each cerebellar subregion with a standard seed-voxel approach for each subject in Dataset1 and Dataset2. The FC analysis was carried out by using Resting-State fMRI Data Analysis Toolkit (REST) V1.8 (https://rfmri.org/REST). Specifically, for a given cerebellar ROI, we took it as a seed region. Then we extracted the averaged time course of all voxels within this seed region and extracted the time course of each voxel in the whole brain for each subject. We estimated FC, i.e., Pearson's correlation coefficient r, between the selected seed region and each voxel of the whole brain. After this step, we obtained a whole-brain FC map of each cerebellar ROI for each subject. Then Fisher's r-to-z transform was used to convert the FC map to z-value maps for statistical analysis.

2.6. Constructing cerebellar network (Dataset1 and Dataset2)

We constructed the cerebellar network for each subject in Dataset1 and Dataset2. We first extracted the averaged time series of all voxels within each cerebellar ROI and then calculated Pearson's correlation coefficient r between any two ROIs to generate the intra-cerebellar FC. These calculations generated a 28 × 28 connectivity matrix for each subject and then, this connectivity matrix was applied in the subsequent analysis. By taking all ROIs as nodes and intra-cerebellar FC as edges, we constructed the cerebellar network for each subject in this study.

2.7. Topological properties of the cerebellar network (Dataset1 and Dataset2)

The topological properties of the cerebellar network ($\mathrm{TP}_{cere\text{-}net}$) were estimated for each subject by using the GRETNA software (Wang et al., 2015) (http://www.nitrc.org/projects/gretna/). For each subject, the intra-cerebellar FC matrix was initially transformed into an undirected and unweighted matrix, i.e., a binarized matrix, using a sparsity value. The sparsity value represents the ratio between the total number of edges and the maximum possible number of edges for a given network. In line with previous studies (Cao et al., 2022; Kim et al., 2017), a range of sparsity values was identified from 0.1 to 0.34 with increments of 0.01 for each subject in this study. Only positive FC was considered in the above analysis. Then, based on each binarized matrix under a specific sparsity value, we calculated $\mathrm{TP}_{cere\text{-}net}$ including four global parameters: clustering coefficient (C_w), characteristic path length (L_w), global efficiency (E_glob) and local efficiency (E_loc) of the cerebellar network, as well as two nodal parameters: the nodal strength and the nodal efficiency of cerebellar regions. In order to avoid the specific selection of a sparsity value, we applied an area under the curve (AUC) approach to estimate the global and nodal parameter value within the defined threshold range. This method was widely used in investigating the topological properties of functional network based on graph theory (Liu et al., 2021; Sulpizio et al., 2020a; Wang et al., 2010). Detailed definitions and mathematical descriptions of these global and nodal parameters are listed in Supplementary Table S3.

2.8. Cerebello-cortical and cerebello-subcortical FC measure (Dataset3)

We estimated cerebello-cortical FC by using a standard ROI-wise approach for each subject in Dataset3. Here, the cortical ROIs were extracted from the Automated Anatomical Labelling (AAL, version3) atlas. As we have mentioned above (*2.4. Definition of ROIs*), the AAL atlas includes 86 cortical regions in two hemispheres. For each subject in Dataset3, we first extracted the averaged time series of all voxels within each posterior cerebellar ROI (including bilateral VI, CrusI, CrusII, VIIb, VIIIa, VIIIb and IX) and within each cortical ROI. Next, we estimated Pearson's correlation coefficient r between the time series of each cerebellar ROI and each cortical ROI to obtain a cerebello-cortical FC. Finally, we obtained a dimension of 14 × 86 cerebello-cortical FC matrix for each subject. Similarly, we estimated cerebello-subcortical FC by extracting the averaged time series of all voxels within each posterior cerebellar ROI and each subcortical ROI (Melbourne Subcortex Atlas, the second hierarchical scale of total 32 ROIs, see *2.4 Definition of ROIs*), and then calculated the Pearson's correlation coefficient r between the time series of each cerebellar ROI and each subcortical ROI to obtain a cerebello-subcortical FC matrix for each subject. The dimension of the cerebello-subcortical was 14 × 32.

2.9. Statistical analyses

We applied two sample t-test to detect the difference in whole-brain FC map of cerebellar subregion between monolinguals and bilinguals. We determined the clusters showing statistic between-group difference with the following criteria: (1) significant threshold $p <$ .05 with the false discovery rate (FDR); (2) the number of voxels in each cluster should be more than 100 voxels; (3) peak voxel of the cluster is located in the gray matter. In a single statistical test, the standard significance threshold of $p <$ .05 is commonly used to control the false-positive (Type-I) error rate at 5% (Bennett et al., 2009; Lieberman & Cunningham, 2009). However, in neuroimaging research, statistical tests are conducted across thousands of voxels throughout the whole brain, raising concerns about multiple comparisons. Since each voxel undergoes a separate statistical test, applying a standard $p <$ .05 threshold without correction could lead to an inflated false-positive rate across the brain. To address this, we applied FDR correction to control for Type-I errors. In addition, we used a nonparametric permutation t-test to determine the difference in $\mathrm{TP}_{cere\text{-}net}$ between monolinguals and bilinguals. Briefly, for a given parameter (such as C_w, L_w, E_glob, E_loc, the nodal strength or the nodal efficiency), we randomly paired its values between monolinguals and bilinguals to generate two new groups. Next, we recalculated the mean value of two new groups and estimated their difference. This permutation was repeated 5,000 times to obtain the empirical distribution of the difference between paired new groups. We then selected a significant level at $p <$ .05 to determine the significant difference between monolinguals and bilinguals at 95% of the empirical distribution in a two-tailed test.

We applied a multiple regression analysis to investigate how the AoA-L2, Immersion-L2, PL-L2 and Usage-L2 (at home and in social settings) modulate the functional neuroplasticity of the cerebellum. We first examined whether four factors of bilingual experiences exhibited multicollinearity by calculating the variance inflation factor (VIF). The result showed that VIFs <5, which means that there is no multicollinearity (Johnston, 1984). Then, we estimated two kinds of models by applying the multiple regression analysis to examine the effects of bilingual experiences on the cerebello-cortical FC (Model 1) and the cerebello-subcortical FC (Model 2). The AoA-L2, Immersion-L2, PL-L2 or Usage-L2 (at home or in social settings) were considered as independent variables; the FC was considered as the dependent variable; and age, sex, L1 spoken, any continued exposure to a third (or more) language and the mean FD parameter of head-motion were run as nuisance covariates in each model. Each bilingual experience (AoA-L2, Immersion-L2, PL-L2 or Usage-L2) was analyzed individually, controlling for the effects of the other factors and nuisance covariates in the multiple regression analysis. The permutation test was used to examine the statistical significance of each model and whether there is a significant main effect of each bilingual experience on cerebellar FC. A statistical test for the main effect will be performed only if the model reaches statistical significance. First, we used the real data of all subjects in the multiple regression analysis to calculate the F-value (F_0) and the t-value (t_0). Then we randomly shuffled the data within the independent variable, the nuisance covariates and the dependent variable across all subjects in each model, and repeated this permutation 5,000 times in the multiple regression analysis to generate the permuted *F*-value and *t*-value. We tallied the number of times (S_F and S_t) when the permuted *F*-value and *t*-value exceeded the original F_0 and t_0. We computed *p*-values ($p = S_F/5000$ and $p = S_t/5000$) to assess the statistical significance of each model and the main effect of bilingual experience on FC, with a significance level set at $p < 0.05$ for both. The multiple regression analysis was performed by using the *regress()* function in the MATLAB software (https://www.mathworks.com/products/matlab.html). Figure 1 shows the flowchart of analysis in this study.

3. Results

3.1. Whole-brain FC map of the cerebellum

We examined the difference in whole-brain FC of different cerebellar subregions between monolingual individuals and bilingual individuals. Statistical analysis revealed that monolinguals exhibited significantly higher FC compared to bilinguals ($p < 0.05$, FDR correction) (Figure 2A and Table 2). More specifically, monolinguals showed significantly higher FC between the right cerebellar lobules V, VI and VIIIa and the right superior temporal gyrus (STG.R) compared to bilinguals. Furthermore, monolinguals also demonstrated significantly higher FC between the left lobule IX, right lobules V and VIIIb and several cortical regions involved in language functions, such as the left inferior frontal gyrus (opercular part, IFGoperc.L), middle frontal gyrus (MFG.L), STG.L and middle temporal gyrus (MTG.L), in comparison to bilinguals. Regarding the bilateral lobules VIIIa, VIIIb, right lobules V, IX and X, these cerebellar subregions exhibited significantly higher FC with the right postcentral gyrus (PoCG.R).

3.2. Topological properties of the cerebellar network

Figure 2B and Supplementary Table S4 show significant differences in global and nodal parameters of the cerebellar networks between monolinguals and bilinguals. Statistical analysis ($p < .05$, 5,000 permutations) revealed a significantly higher global efficiency ($p = .001$) in monolinguals compared to bilinguals. In addition, bilinguals demonstrated significantly higher characteristic path length ($p = .002$) than monolinguals. No significant between-group difference in clustering coefficient ($p = .189$) and local efficiency ($p = .065$) was found. For nodal parameters, we found in monolinguals, the nodal strength was significantly higher in the cerebellar lobules V.R, VIIIa.L and bilateral VIIIb, but lower in the CrusII.R compared to bilinguals.

3.3. AoA-L2 and functional neuroplasticity of the cerebellum

Bilinguals who learned L2 earlier (i.e., lower value of AoA-L2) showed an increase in cerebello-cortical FC involving the lobules VI.R, CrusI.R and the right precentral gyrus (PreCG.R); the lobule VIIIa and the right fusiform (FFG.R); the lobule VIIIb and the STG.L; and the lobule IX.R and the right rolandic operculum (ROL.R). However, early bilinguals showed decreased cerebello-cortical FC between the bilateral lobules IX and the angular (ANG) and between the lobule IX.R and the right posterior cingulate gyrus (PCG.R). For the cerebello-subcortical FC, an increase in AoA-L2 was associated with an increase in FC involving the lobule VI.L and the dorsoanterior part of the right thalamus (daTHA.R), the lobule CrusII.R and the posterior part of the right caudate (pCAU.R). In addition, late bilinguals (i.e., higher value of AoA-L2) showed increased cerebello-subcortical FC between bilateral IX and the anterior part of the left caudate (aCAU.L) and the daTHA. Figure 2C and Table 3 show the results of the relationship between the cerebello-cortical FC and the AoA-L2. The results of the relationship between the cerebello-subcortical FC and the AoA-L2 are shown in Table 5.

3.4. Immersion-L2 and functional neuroplasticity of the cerebellum

We found that decreased cerebellar FC was associated with increased Immersion-L2 in bilinguals (Figure 2C and Table 3). In particular, decreased cerebello-cortical FC involves the cerebellar lobules VI, VIIb.L, VIIIa, VIIIb and IX.R and different parts of the orbitofrontal cortex (OFC) (anterior, posterior and lateral: OFCant, OFCpost and OFClat) in bilinguals. Decreased cerebello-subcortical FC between the lobules VIIb, VIIIa.R, VIIIb.R and the ANG.L was related to increased Immersion-L2. Moreover, with Immersion-L2 increased, bilinguals exhibited decreased cerebello-subcortical FC involving the lobules VIIb, VIIIa, VIIIb, and the posterior part of the hippocampus (pHIP). Decreased cerebello-subcortical FC between the lobules CrusI.L, VIIb.L, VIIIa.L, VIIIb, IX.R and the posterior part of the globus pallidus (pGP) also was related to increased Immersion-L2 in bilinguals (Table 5).

3.5. PL-L2 and functional neuroplasticity of the cerebellum

Increased cerebellar FC was associated with higher PL-L2 in bilinguals (Figure 2C and Table 3). Specifically, as PL-L2 increased, bilinguals exhibited increased cerebello-cortical FC between the lobule VI.L and the bilateral posterior cingulate cortex (PCC), as well as between the lobule VIIb.L and the PCC.R. Moreover, higher PL-L2 was related to stronger cerebello-cortical FC between bilateral lobules IX and the bilateral OFCpost and the left temporal pole (superior temporal gyrus, TPOsup). In addition to these cerebello-cortical connectivity patterns, higher PL-L2 was also associated with stronger cerebello-subcortical FC. For example, bilinguals with higher PL-L2 showed increased FC between the lobules CrusI.L and VIIb.R and the left medial amygdala (mAMY.L), as well as between bilateral lobules IX and the bilateral daTHA (Table 5).

3.6. Usage-L2 and functional neuroplasticity of the cerebellum

Decreased cerebello-cortical FC was related to increased Usage-L2 at home in bilinguals (Figure 2C and Table 4). For example, decreased cerebello-cortical FC between the lobule IX.R and the left insula (INS.L), PreCG.R and left TPO (middle temporal gyrus, TPOmid.L) were found in bilinguals who used L2 more frequently at home. Similarly, decreased cerebello-cortical FC between the lobules VI.R and CrusI and the PreCG.R, and between the lobules VI.R, VIIb.L and VIIIa and the FFG.R were associated with increased Usage-L2 at home. For those bilinguals who used L2 less at home, we found increased cerebello-subcortical FC between the lobule IX and the mAMY.L (Table 5).

We found the Usage-L2 in social settings modulated the cerebello-cortical FC in bilinguals (Figure 2C and Table 4). That is, bilinguals who used L2 more frequently during social communications were related to increased cerebello-cortical FC between the lobule IX.R and the ROL.L, right olfactory cortex (OLF.R), INS.L and FFG.R. Also, increased Usage-L2 in social

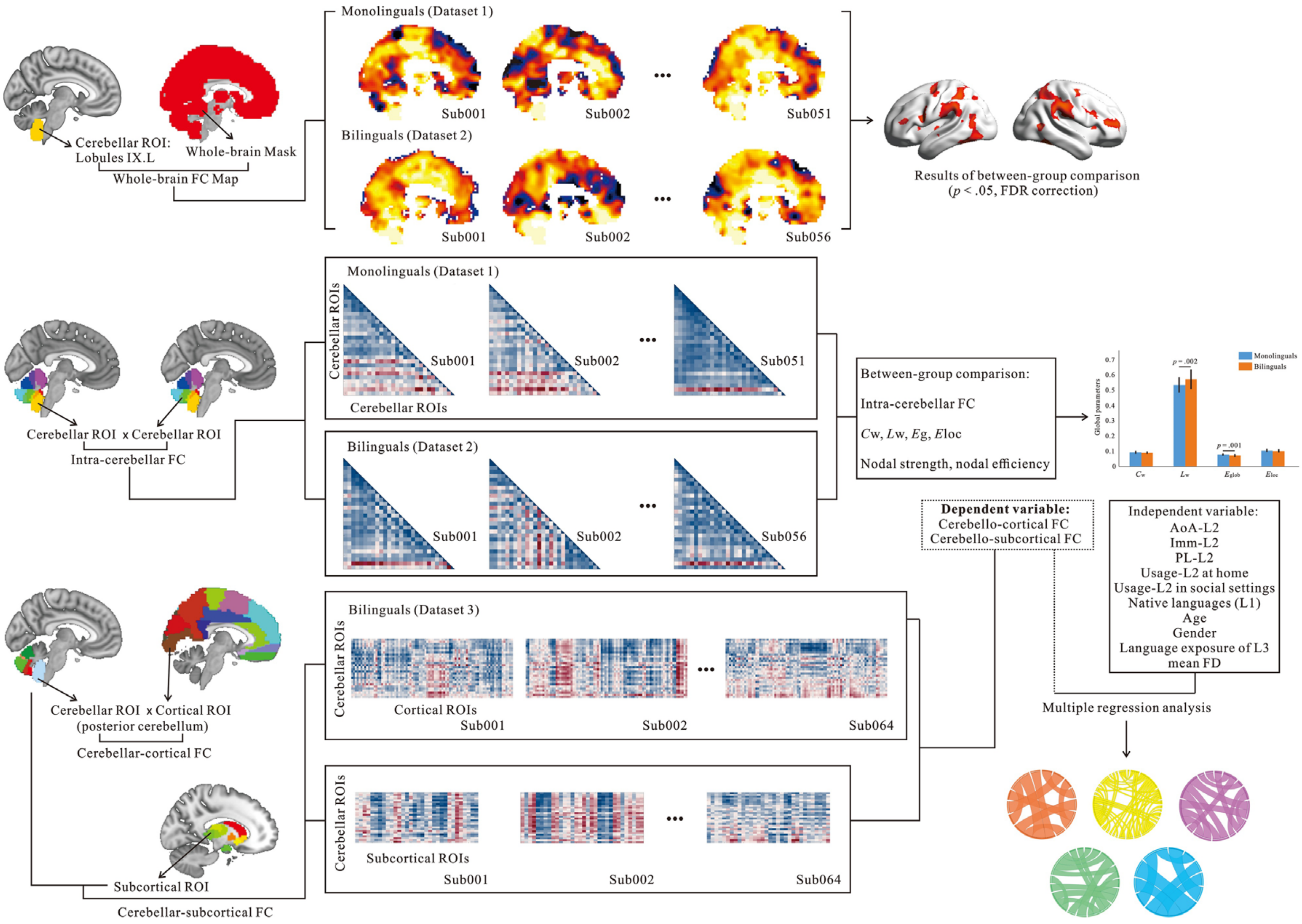

Figure 1. The flowchart for analyzing the functional neuroplasticity of the cerebellum in this study.

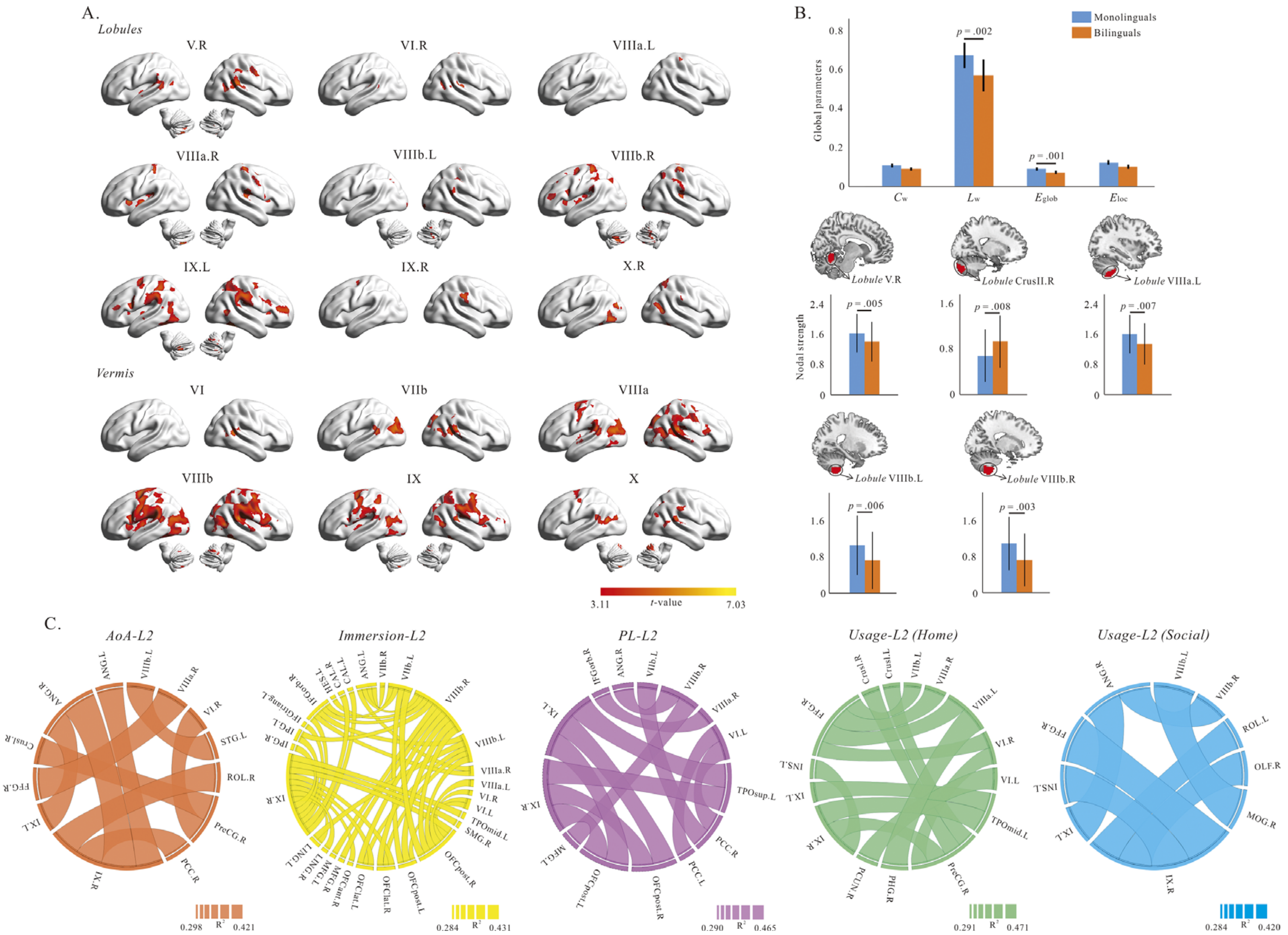

Figure 2. Significant difference in resting-state functional connectivity (FC) map of the cerebellum (A) and topological properties of the cerebellar network (B) between monolinguals and bilinguals. Significant effect of bilingual experiences (AoA-L2, orange; Immerison-L2, yellow; PL-L2, purple; Usage-L2 at home, green; Usage-L2 in social settings, blue) on cerebellar FC (C). The bar corresponds to the mean value and the error bar to the standard deviation. Abbreviations: AoA-L2, age of second language acquisition; PL-L2, proficiency level of second language; C_w, Clustering coefficient; L_w, characteristic path length; E_{glob}, global efficiency; E_{loc}, local efficiency; L, left; R, right. The corresponding abbreviation and full name of cortical and subcortical regions are listed in Tables 2–4.

Table 2. Cluster locations and peak coordinates corresponding to the resting-state functional connectivity (FC) based on cerebellar region

Seed region	Cluster location	Cluster size (# voxels)	*t*-value	Peak coordinate in MNI space			Seed region	Cluster location	Cluster size (# voxels)	*t*-value	Peak coordinate in MNI space		
				x	y	z					x	y	z
Lobules													
V.R	Lobule V.L	496	5.23	−6	−57	−21	VIIIb.L	Lobule VIIIa.R	164	5.27	39	−45	−51
	Lobule VIII.R	128	5.04	39	−39	−54		FFG.R	183	4.48	33	−57	−15
	STG.L	100	4.62	−45	−15	3		CUN.L	1624	5.38	−3	−78	36
	MTG.L	374	5.04	−45	−51	9		PoCG.R	368	6.28	27	−33	45
	STG.R	784	5.54	54	−39	18	VIIIb.R	Lobule VIIIa.R	461	5.94	39	−45	−51
	PoCG.R	163	4.94	12	−36	69		Lobule VIIb.L	301	4.66	−36	−60	−51
VI.R	STG.R	260	5.46	39	−30	9		PoCG.R	4383	6.72	27	−33	45
	MTG.L	121	4.84	−45	−48	15		MFG.L	256	4.59	−30	27	27
	PCUN.L	116	4.66	−6	−78	39		IFGoperc.L	134	4.76	−45	6	18
	PCL.R	204	5.28	9	−36	69	IX.L	Lobule CrusI.R	247	4.99	48	−45	−36
VIIIa.L	CUN.L	111	4.82	−9	−75	30		Lobule CrusI.L	3877	5.25	−51	−51	−36
	PoCG.R	116	7.03	27	−33	45		ITG.R	815	5.51	45	−48	−15
VIIIa.R	Lobule VIIb.L	131	5.64	−33	−60	−51		IFGoperc.L	458	4.87	−51	6	18
	STG.L	271	5.32	−45	−15	0		PreCG.L	263	4.80	−27	−9	60
	PUT.R	143	5.06	27	3	3		PreCG.R	144	4.84	30	−9	54
	STG.R	315	4.88	39	−27	9	IX.R	PoCG.R	179	4.71	27	−36	45
	CUN.L	227	4.68	−9	−75	21		SMA.L	138	4.74	−12	−12	63
	ROL.L	118	4.51	−36	−27	18	X.R	FFG.R	124	5.26	36	−51	−15
	PreCG.R	144	4.65	57	3	39		MOG.L	345	5.29	−42	−84	18
	SMA.R	195	5.08	9	−3	60		MTG.R	113	5.17	48	−57	6
	PoCG.R	475	6.56	27	−33	45		PoCG.R	247	5.55	27	−33	45
Vermis													
VI	STG.R	268	5.44	51	−39	18	IX	STG.L	166	4.35	−39	−6	−12
VIIb	STG.R	1972	5.66	54	−39	18		SOG.R	5527	5.70	27	−66	21
	MTG.L	212	5.02	−45	−48	15		IPG.L	161	5.08	−33	−45	48
VIIIa	PUT.R	143	4.13	30	6	3	X	Lobule VIIIa.L	111	4.95	−24	−63	−48
	CUN.R	7120	5.83	9	−75	33		FFG.L	1335	5.14	−36	−36	−21
	IFGtriang.R	145	4.13	54	18	15		PUT.R	102	4.52	33	6	−3
VIIIb	Lobule VIIb.L	139	4.30	−15	−72	−48		MTG.L	437	5.08	−42	−63	18
	CUN.R	12557	5.96	15	−78	33		STG.R	378	4.87	54	−36	18
IX	Lobule VIIIa.L	134	4.58	−27	−57	−48		PCUN.R	345	5.00	15	−39	45
	Lobule V.R	668	4.99	12	−54	−24		SMA.L	187	4.23	−12	−12	63

Note: The statistical significance was set at $p < .05$ (FDR correction).

Abbreviations: L, left; R, right; STG, superior temporal gyrus; MTG, middle temporal gyrus; PoCG, postcentral gyrus; PCUN, precuneus; PCL, paracentral lobule; CUN, Cuneus; PUT, putamen; ROL, rolandic operculum; PreCG, precentral gyrus; SMA, supplementary motor area; FFG, fusiform gyrus; MFG, middle frontal gyrus; IFGoperc, inferior frontal gyrus (opercular part); ITG, inferior temporal gyrus; SOG, superior occipital gyrus; IPG, inferior parietal gyrus.

settings was associated with increased cerebello-cortical FC between the lobule VIIIb.L and the right middle occipital gyrus (MOG.R). However, increased cerebello-cortical FC involving the lobules VIIIa.R and IX.L and the ANG.R was found in bilinguals with decreased Usage-L2 in social settings. In addition, increased cerebello-subcortical FC between the lobule IX.L and the bilateral mAMY was related to increased Usage-L2 in social settings (Table 5).

4. Discussion

In this study, we investigated the difference in cerebellar FC between bilinguals and monolinguals, then examined the effect of AoA-L2, Immersion-L2, PL-L2 and Usage-L2 on functional neuroplasticity of the posterior cerebellum in bilinguals. We found stronger cerebellar FC between the right cerebellar lobules including V, VI and VIIIa and the temporal lobe region, in monolinguals compared to bilinguals. Also, monolinguals exhibited

Table 3. Size effects (β), t- and p-value of AoA-L2, Immersion-L2, and PL-L2 are reported for each significant result ($p < .05$, permutation test) in the cerebello-cortical FC

FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	t	p	FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	t	p
AoA-L2											
VI.R	PreCG.R	−1.470	0.638	−2.305	.021	IX.R	ROL.R	−1.876	0.891	−2.105	.035
CrusI.R	PreCG.R	−1.754	0.811	−2.162	.031		PCC.R	1.563	0.724	2.159	.031
VIIIa.R	FFG.R	−1.343	0.576	−2.330	.020		ANG.L	1.734	0.683	2.539	.011
VIIIb.L	STG.L	−1.532	0.744	−2.059	.039		ANG.R	2.197	0.700	3.140	.002
IX.L	ANG.R	2.179	0.804	2.711	.007						
Immersion-L2											
VI.L	OFCpost.L	−0.089	0.038	−2.317	.020	VIIIb.R	OFCpost.R	−0.153	0.045	−3.414	.001
	OFCpost.R	−0.110	0.038	−2.913	.004		OFClat.L	−0.098	0.042	−2.328	.020
VI.R	OFCpost.R	−0.099	0.040	−2.508	.012		OFClat.R	−0.104	0.042	−2.486	.013
VIIb.L	IFGorb.R	−0.074	0.036	−2.062	.039		IPG.L	−0.111	0.043	−2.608	.009
	OFCpost.L	−0.117	0.038	−3.063	.002		ANG.L	−0.087	0.041	−2.127	.033
	OFCpost.R	−0.128	0.036	−3.589	.000		HES.L	−0.085	0.037	−2.280	.023
	ANG.L	−0.098	0.043	−2.271	.023	IX.R	IFGtriang.L	−0.094	0.043	−2.201	.028
VIIb.R	ANG.L	−0.117	0.045	−2.588	.010		IFGorb.R	−0.097	0.046	−2.113	.035
VIIIa.L	OFCpost.R	−0.092	0.036	−2.573	.010		OFCant.R	−0.087	0.043	−2.031	.042
VIIIa.R	IFGorb.R	−0.103	0.037	−2.811	.005		OFCpost.R	−0.091	0.043	−2.137	.033
	ANG.L	−0.095	0.043	−2.213	.027		OFClat.L	−0.095	0.040	−2.402	.016
VIIIb.L	IFGorb.R	−0.107	0.039	−2.723	.006		OFClat.R	−0.116	0.043	−2.726	.006
	OFCpost.R	−0.147	0.047	−3.140	.002		CAL.L	−0.097	0.040	−2.401	.016
	OFClat.L	−0.093	0.043	−2.148	.032		CAL.R	−0.101	0.040	−2.515	.012
	OFClat.R	−0.097	0.042	−2.297	.022		LING.L	−0.103	0.042	−2.478	.013
	LING.L	−0.081	0.041	−2.004	.045		LING.R	−0.090	0.039	−2.340	.019
VIIIb.R	MFG.L	−0.103	0.040	−2.542	.011		IPG.L	−0.104	0.046	−2.255	.024
	MFG.R	−0.093	0.045	−2.098	.036		IPG.R	−0.102	0.048	−2.135	.033
	IFGorb.R	−0.118	0.040	−2.957	.003		SMG.R	−0.103	0.052	−1.998	.046
	OFCpost.L	−0.121	0.041	−2.922	.003		TPOmid.L	−0.077	0.035	−2.205	.027
PL-L2											
VI.L	PCC.L	1.123	0.508	2.211	.027	IX.L	OFCpost.L	1.374	0.518	2.653	.008
	PCC.R	1.076	0.463	2.324	.020		OFCpost.R	1.362	0.559	2.438	.015
VIIb.L	PCC.R	1.045	0.498	2.100	.036		TPOsup.L	1.243	0.598	2.079	.038
VIIIa.R	IFGorb.R	1.002	0.461	2.176	.030	IX.R	OFCpost.L	1.244	0.433	2.874	.004
VIIIb.R	MFG.L	1.053	0.508	2.071	.038		OFCpost.R	1.104	0.537	2.057	.040
	ANG.R	1.066	0.525	2.031	.042		TPOsup.L	1.136	0.552	2.058	.040

Abbreviations: L, left; R, right; PreCG, precentral gyrus; FFG, fusiform gyrus; STG, superior temporal gyrus; ANG, angular gyrus; ROL, rolandic operculum; PCC, posterior cingulate gyrus; OFCant, anterior orbitofrontal cortex; OFCpost, posterior orbitofrontal cortex; OFClat, lateral orbitofrontal cortex; IFGorb, inferior frontal gyrus (orbital part); LING, lingual gyrus; MFG, middle frontal gyrus; IPG, inferior parietal gyrus; HES, Heschel's gyrus; IFGtriang, inferior frontal gyrus (triangular part); CAL, calcarine fissure and surrounding cortex; SMG, supramarginal gyrus; TPOmid, temporal pole (middle temporal gyrus); TPOsup, temporal pole (superior temporal gyrus).

stronger cerebellar FC than bilinguals between the lobules V, VIIIb and IX, and several cortical language regions. These results reflected different connectivity patterns of the cerebellum between bilinguals and monolinguals. For the bilingual experiences, we found that AoA-L2 mainly modulated cerebello-cortical FC involving the lobules VI.R, CrusI.R, VIIIa.R, VIIIb.L and bilateral IX. Cerebellar FC between the VI.L, CrusII.R and bilateral IX and several subcortical regions was positively associated with AoA-L2. Bilinguals with increased Immersion-L2 were related to decreased cerebellar FC between the lobules VI, VIIb.L, VIII and IX.R and different parts of the OFC. Higher PL-L2 was associated with stronger cerebellar FC between the lobules VI and VIIb and the PCC. For the Usage-L2, we found that bilinguals who used L2 more frequently at home showed decreased cerebellar FC involving the

Table 4. Size effects (β), *t*- and *p*-value of Usage-L2 at home and in social settings are reported for each significant result ($p < .05$, permutation test) in the cerebello-cortical FC

FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	*t*	*p*	FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	*t*	*p*
Usage-L2 at home											
VI.R	PreCG.R	−1.777	0.593	−2.995	.003	VIIIa.L	FFG.R	−1.704	0.597	−2.855	.004
	FFG.R	−0.703	0.336	−2.096	.036	VIIIa.R	FFG.R	−1.374	0.536	−2.562	.010
CrusI.L	PreCG.R	−2.168	0.817	−2.653	.008	IX.L	TPOmid.L	−1.317	0.654	−2.015	.044
CrusI.R	PreCG.R	−2.046	0.755	−2.712	.007	IX.R	PreCG.R	−1.772	0.805	−2.201	.028
VIIb.L	FFG.R	−1.147	0.562	−2.041	.041		INS.L	−1.631	0.782	−2.087	.037
VIIIa.L	PHG.R	−1.474	0.663	−2.225	.026		TPOmid.L	−1.676	0.621	−2.698	.007
Usage-L2 in social settings											
VIIIa.R	ANG.R	−0.550	0.257	−2.145	.032	IX.R	OLF.R	0.636	0.245	2.596	.009
VIIIb.L	MOG.R	0.540	0.249	2.171	.030		INS.L	0.668	0.268	2.490	.013
IX.L	ANG.R	−0.525	0.256	−2.046	.041		FFG.R	0.506	0.237	2.136	.033
IX.R	ROL.L	0.580	0.275	2.109	.035						

Abbreviations: L, left; R, right; PreCG, precentral gyrus; FFG, fusiform gyrus; PHG, parahippocampal gyrus; TPOmid, temporal pole (middle temporal gyrus); INS, insula; ANG, angular gyrus; MOG, middle occipital gyrus; ROL, rolandic operculum; OLF, olfactory cortex.

lobules VI.R, VIIb.L, bilateral VIIIa and the FFG.R. In addition, Usage-L2 in social settings modulated the cerebellar FC between the lobule IX.R and the INS.L. Our findings suggested that AoA-L2, Immersion-L2, PL-L2 and Usage-L2 influence the functional neuroplasticity of the posterior cerebellum in different ways.

4.1. Difference in cerebellar FC and topological properties of the cerebellar network between monolinguals and bilinguals

We found significantly stronger cerebellar FC between the right cerebellar lobule VI and right STG, and between right lobule VIIIa and bilateral STG in monolinguals compared to bilinguals. These results reflected that different language experiences modulated cerebello-cortical FC. The lobules VI and VIIIa have been implicated in language-related functions. For example, a previous meta-analysis study showed that the right lobule VI was related to phonological processing during English tasks (Tan et al., 2005). For the right lobule VIIIa, its greater activation was observed in the semantic processing task (D'Mello et al., 2020; Wu et al., 2012). In addition, both lobules VI and VIIIa are involved in verbal working memory tasks but play two distinct roles; the lobule VI is involved in articulatory rehearsal, while lobule VIIIa is implicated in the maintenance and storage of information (Chen & Desmond, 2005; Mariën et al., 2014). The STG plays a fundamental role in different aspects of speech processing, such as acoustic-phonetic analysis, prosodic interpretation and integration of multimodal input for speech comprehension (Yi et al., 2019). Additionally, the STG is essential for encoding temporal cues in speech signals and generating context-dependent phonological representations for coherent perception of syllables, words and phrases. It has been shown that the lack of using spoken language may induce decreased FC involving the STG. Accordingly, the intrinsic FC between the lobules VI and VIIIa and the STG may be related to phonological and semantic processing during speech expression. Previous studies have shown differences in neural activation involving these relevant language processes between monolinguals and bilinguals (Brice et al., 2023; Kovelman et al., 2008; Marian et al., 2014). In line with these previous findings, our results further suggested that different L1 and L2 experiences modulated intrinsic connectivity patterns of cerebellar and cortical regions relating to phonological and semantic processing.

Compared to monolinguals, bilinguals showed significantly weaker FC between the lobules VIIIb.R and IX.L and the IFGoperc.L. The VIIIb and IX have been traditionally linked to balance control and response to tactile stimulation (Bushara et al., 2001; Koppelmans et al., 2017). However, the structural study found that increased GMV of cerebellar lobules VIII (consisting of VIIIa and VIIIb) and IX were related to better cognitive performance in vocabulary, reading, working memory and set-shifting (Moore et al., 2017). In addition, the GMV of cerebellar lobule VIIIb showed a negative correlation with the language composite scores (D'Mello et al., 2016). A recent structural study found that significant difference in GMV of the VIIIb and IX between monolinguals and bilinguals suggested the effect of bilingual experiences on the structural neuroplasticity of these cerebellar regions (Jin et al., 2023; Schug et al., 2022). These results reflected that the lobules VIIIb and IX are not only implicated in motor functions but also in relevant language functions. For the IFGoperc.L, it plays an important role in language processes. Cytoarchitecturally, this region is known as Brodmann area 44 (BA44), which is a posterior part of Broca's area involving speech production. The IFGoperc is also related to recognizing the tone of voice during spoken in L1 (Schremm et al., 2018). Stronger cerebello-cortical FC between lobules VIIIb.R and IX.L and IFGoperc.L may reflect that monolinguals are more sensitive to spoken in L1 than bilinguals. These results were similar to a previous study showing stronger FC between the dorsal anterior cingulate cortex (dACC) and other cortical spoken regions (STG.L and ROL.L) in monolinguals compared to bilinguals (Li et al., 2015).

We observed significantly higher E_{glob} in the cerebellar network for monolinguals compared to bilinguals. This finding was similar to previous findings indicating higher E_{glob} in monolinguals compared to bilinguals (Amoruso et al., 2024), suggesting that bilingual experience consistently influences brain structure and function. Monolinguals typically rely on a more unified cerebellar network dedicated to a single language, facilitating more efficient global

Table 5. Size effects (β), *t*- and *p*-value of bilingual experiences are reported for each significant result ($p < .05$, permutation test)

FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	*t*	*p*	FC		β ($\times 10^{-2}$)	St. Error ($\times 10^{-2}$)	*t*	*p*
AoA-L2											
VI.L	daTHA.R	1.936	0.640	3.024	.002	IX.R	pHIP.R	1.547	0.745	2.077	.038
CrusII.R	pCAU.R	1.295	0. 623	2.078	.038		daTHA.R	2.212	0.973	2.273	.023
IX.L	daTHA.R	2.765	1.055	2.620	.009		aCAU.R	2.001	0.890	2.258	.024
	aCAU.R	2.515	1.025	2.454	.014		pHIP.L	1.754	0.802	2.187	.029
	vaTHA.L	2.010	1.009	2.081	.037		daTHA.L	3.015	1.019	2.959	.003
	daTHA.L	3.113	1.024	3.040	.002		aCAU.L	2.793	0.957	2.918	.004
	aCAU.L	2.820	1.079	2.613	.009						
Immersion-L2											
VI.L	vaTHA.L	−0.069	0.031	−2.219	.026	VIIIa.R	pHIP.R	−0.124	0.044	−2.856	.004
CrusI.L	vaTHA.L	−0.065	0.032	−2.016	.044	VIIIb.L	pHIP.R	−0.103	0.049	−2.121	.034
	pGP.L	−0.112	0.039	−2.889	.004		dpTHA.R	−0.116	0.054	−2.161	.031
CrusI.R	pPUT.R	−0.075	0.037	−2.048	.041		pHIP.L	−0.099	0.050	−1.973	.049
	aGP.L	−0.088	0.039	−2.244	.025		pGP.L	−0.117	0.047	−2.481	.013
CrusII.L	mAMY.L	−0.082	0.039	−2.098	.036	VIIIb.R	pHIP.R	−0.123	0.047	−2.620	.009
CrusII.R	aPUT.R	−0.091	0.036	−2.526	.012		dpTHA.R	−0.114	0.053	−2.170	.030
	pCAU.R	−0.068	0.033	−2.087	.037		pPUT.R	−0.085	0.038	−2.237	.025
VIIb.L	pHIP.R	−0.134	0.038	−3.502	.000		pHIP.L	−0.123	0.051	−2.424	.015
	pHIP.L	−0.084	0.039	−2.155	.031		vpTHA.L	−0.116	0.049	−2.357	.018
	pGP.L	−0.128	0.042	−3.037	.002		pGP.L	−0.134	0.042	−3.229	.001
VIIb.R	pHIP.R	−0.116	0.040	−2.884	.004		aGP.L	−0.134	0.057	−2.362	.018
	mAMY.L	−0.076	0.036	−2.109	.035	IX.L	pGP.L	−0.010	0.047	−2.131	.033
VIIIa.L	pHIP.R	−0.095	0.038	−2.479	.013	IX.R	vaTHA.R	−0.113	0.049	−2.321	.020
	pGP.L	−0.128	0.040	−3.192	.001		daTHA.L	−0.112	0.053	−2.111	.035
	aGP.L	−0.107	0.048	−2.218	.027		pGP.L	−0.128	0.044	−2.916	.004
PL-L2											
CrusI.L	mAMY.L	1.081	0.516	2.094	.036	IX.R	vaTHA.R	1.401	0.612	2.288	.022
CrusI.R	pCAU.R	0.761	0.374	2.038	.042		daTHA.R	1.481	0.642	2.309	.021
VIIb.R	mAMY.L	0.966	0.457	2.116	.034		pGP.R	0.925	0.452	2.047	.041
IX.L	daTHA.R	1.807	0.696	2.597	.009		aCAU.R	1.282	0.587	2.185	.029
	daTHA.L	1.759	0.675	2.606	.009		daTHA.L	1.392	0.672	2.073	.038
Usage-L2 at home											
IX.L	mAMY.L	−1.843	0.778	−2.369	.018	IX.R	mAMY.L	−1.755	0.714	−2.459	.014
IX.R	pGP.R	−1.599	0.637	−2.509	.012						
Usage-L2 in social settings											
IX.L	mAMY.R	0.529	0.258	2.049	.040	IX.L	daTHA.L	−0.741	0.327	−2.269	.023
	mAMY.L	0.776	0.267	2.906	.004	IX.R	mAMY.L	0.730	0.245	2.982	.003

Abbreviations: L, left; R, right; daTHA, dorsoanterior thalamus; pCAU, posterior caudate; aCAU, anterior caudate; vaTHA, ventroanterior thalamus; pHIP, posterior hippocampus; pGP, posterior globus pallidus; pPUT, posterior putamen; aGP, anterior globus pallidus; mAMY, medial amygdala; aPUT, anterior putamen; dpTHA, dorsoposterior thalamus; vpTHA, Ventroposterior thalamus.

integration of cerebellar regions. In contrast, bilinguals exhibit different neural activation of the cerebellum for L1 and L2 processing (Pillai et al., 2004), which may result in a more complex and less integrated cerebellar network. The increased specialization of neural activation for two languages may induce a trade-off, where bilinguals exhibit stronger internal modular organization but at the cost of the E_{glob} of the cerebellar network. Similar patterns have been observed in training-induced neuroplasticity, where long-term expertise leads to more selective and specialized neural organization. For example, elite gymnasts and professional dancers showed reduced global topological properties, reflecting increased automaticity and efficiency within task-relevant networks (Amoruso et al., 2022; Wang et al., 2016). Similarly, in bilinguals, the demand for processing two languages may drive a reorganization of cerebellar connectivity, leading to decreased global integration of the cerebellar network (Amoruso et al., 2024).

4.2. Cerebellar FC and AoA-L2

We found cerebello-cortical FC involving subregions of the posterior cerebellum and several cortical regions that was negatively associated with the AoA-L2. For example, early bilinguals exhibited stronger FC between the lobules VI.R, CrusI.R and the PreCG.R. Previous studies employing fluency-based tasks, such as verb generation, verbal fluency and verbal working memory (Desmond et al., 1997; Frings et al., 2006; McDermott et al., 2003; Stoodley & Schmahmann, 2009; Vias & Dick, 2017), have identified the involvement of the VI.R and CrusI.R in phonological and semantic processing, while the PreCG.R has been implicated in language switching relative to single-language production (Luk et al., 2012; Yuan et al., 2021). During early bilingual acquisition, individuals frequently switch between the phonological and semantic representations of two languages. This continuous linguistic alternation may impose greater demands on neural resources, which induces stronger FC between these cerebellar and cortical regions. These results were similar to a previous study that found significantly higher intra-FC of “phonological module” and “semantic module” in early bilinguals than in late bilinguals (Liu et al., 2017). Combined with these findings, the observed stronger cerebello-cortical FC between the VI.R and CrusI.R and PreCG.R in early bilinguals may reflect the neural coordination required for phonological and semantic processing. This increased cerebellar FC may facilitate the rapid formation of phonological-semantic associations, which is crucial for new language learning in early bilinguals. Martin et al. (2013) found that early bilingual learners of an L3 exhibited different neural activation patterns compared to late bilingual L3 learners, which may underlie some of the advantages early bilinguals demonstrate in learning a new language. In addition, a previous study has shown stronger FC between the cerebellum and the IFG in simultaneous bilinguals (who acquire L1 and L2 from birth) compared to sequential bilinguals (who acquire L2 after age 5) (Berken et al., 2016). Early bilinguals exhibit higher dynamic FC between the cerebellum and the orbital part of the IFG compared to late bilinguals (Liu et al., 2020). These findings highlight the potential impact of early bilingual experience on cerebello-prefrontal FC. However, previous studies have not specified which subregion of the cerebellum is involved in neural pathways related to AoA-L2 in bilinguals. In this study, we examined the effect of AoA-L2 on cerebello-cortical FC between each subregion of the posterior cerebellum and cortical regions. Our findings indicate that AoA-L2 modulates the cerebello-cortical neural circuit, involving not only the IFG but also the posterior part of the frontal lobe (i.e., PreCG). These results enhance our understanding of how AoA-L2 shapes the neural coupling between the posterior cerebellum and language-related cortical regions.

In addition, we found that cerebello-subcortical FC between bilateral IX and the aCAU was positively associated with AoA-L2. The cerebellar lobule IX is part of the default mode network (DMN) (Diedrichsen et al., 2019). The DMN plays a crucial role in complex cognitive functions such as memory, abstract thought and self-referential processing, while typically exhibiting reduced activity during attention-demanding tasks (Smallwood et al., 2021). A previous study found higher connectivity within the DMN in late bilinguals compared to early bilinguals, which suggests that late bilinguals require greater cognitive effort for L2 learning than early bilinguals (Gold, 2018). The caudate has been implicated in both cognitive and language control (Grahn et al., 2008; Green & Abutalebi, 2013). It contributes to the selection of the appropriate language and inhibition of irrelevant ones in bilinguals. Its involvement in managing lexico-semantic sets based on task demands indicates its role in overarching task-level control in language processing (Green & Abutalebi, 2013). Sulpizio et al., 2020a found that the modulation of FC between the CAU.L and the right cerebellum emerges from the AoA-L2 by PL-L2 interaction, showing that the earlier individuals become bilinguals, the more a higher level of proficiency is associated with weaker cerebello-caudate FC. These findings suggested that early proficient bilinguals may have an enhanced ability to minimize cross-linguistic interference efficiently. In this study, we found stronger FC between the lobule IX and the aCAU, which may reflect the increased cognitive demands of L2 learning and the greater involvement of cognitive control required for language selection and interference inhibition in late bilinguals.

4.3. Cerebellar FC and Immersion-L2

We found that cerebellar FC was negatively associated with Immersion-L2 in bilinguals. Previous studies have reported structural differences in the cerebellum between bilinguals and monolinguals, with several studies indicating greater GMV and density in bilinguals, suggesting adaptations related to the increased cognitive demands of managing two languages (Jin et al., 2023; Schug et al., 2022). According to the DRM, cerebellar GMV is proposed to consistently increase across three stages of bilingual experience: initial exposure, consolidation and peak efficiency (Pliatsikas, 2020). During the second stage (consolidation), cortical expansions are reversed and renormalized, eliminating redundant local connections and optimizing lexical learning and control. This process leads to more efficient neural circuits for language processing (Marin-Marin et al., 2022). In our study, we observed decreased cerebello-cortical FC between cerebellar lobules VI, VIIb.L, VIIIa, VIIIb and IX.R, and the OFC, which was negatively associated with increased Immersion-L2. This may reflect the cortical renormalization process that induces decreased cerebellar-cortical FC. The OFC, particularly the lateral OFC (OFClat), has strong anatomical and functional connections with key language regions, including Broca’s area (BA 44/45) within the IFG, as well as the MTG and STG, which support semantic processing, language comprehension and executive control (Du et al., 2020; Jiang et al., 2024). As Immersion-L2 increases in bilinguals, the brain reorganizes its neural circuits to enhance language processing efficiency, which may lead to a decreased involvement of neural connectivity between cerebellar and cortical regions. Our results were in line with previous findings, which suggest that adaptations related to the length of L2 immersion reflect an increased automation in language control processing with prolonged, intensive exposure to L2 (DeLuca et al., 2019; Linck et al., 2009). This increased automation may underlie the observed negative association between cerebellar FC and Immersion-L2 in our study.

4.4. Cerebellar FC and PL-L2

Our findings revealed that higher PL-L2 was associated with stronger FC between the cerebellar lobules VI.L and VIIb.L and the PCC in bilinguals. These two cerebellar regions play a crucial role in lexical-semantic processing for non-native languages, indicating their involvement in the more demanding cognitive control and language monitoring required when retrieving words in later-learned languages (Mariën et al., 2017). Anatomically, lobules VI and VIIb are closely connected to prefrontal cortical regions, suggesting that activation in these cerebellar regions supports the executive control mechanisms necessary for fluent L2 word retrieval and helps manage interference from other languages during multilingual language production. Similarly, previous studies have indicated that the PCC is involved in lexical-semantic processing (Price, 2010) and may contribute to the integration of semantic and episodic memory, as well as self-referential processing (Binder et al., 2009). Importantly, several studies have demonstrated that engagement of the PCC during L2 language processing is associated with individual PL-L2 (Grant & Li, 2019; Palomar-García et al., 2015; Zhang et al., 2023). For example, Grant and Li (2019) reported that highly proficient L2 learners exhibited greater PCC activation and more organized FC during the semantic decision task, reflecting a shift from effortful, top-down control to more precise, integrated processing. Zhang et al. (2023) found that proficient L2 learners showed stronger PCC synchronization during narrative comprehension, approaching native-like patterns of semantic integration and high-level contextual processing. In our study, stronger FC between the lobules VI and VIIb and the PCC in bilinguals with high PL-L2 may reflect the coordinated engagement of these regions to support precise lexical-semantic retrieval, executive monitoring and semantic-contextual integration. Specifically, the lobules VI and VIIb may contribute to fine-grained control and lexical access, while the PCC provides a hub for semantic convergence and the integration of episodic or contextual cues. The functional integration of neural activity between these regions may therefore reflect a neural adaptation that supports more precise and native-like language use as proficiency increases.

In addition, our results aligned with previous evidence indicating that higher PL-L2 was associated with increased FC and neural activity involving regions implicated in language processing and cognitive control (Mondt et al., 2009; Sulpizio et al., 2020a; Wang et al., 2020). Wang et al. (2020) reported that bilinguals with higher PL-L2 exhibited stronger resting-state and task-based FC among regions supporting language selection, articulation and cognitive control, indicating enhanced integration between semantic and executive systems. Similarly, Sulpizio et al., 2020a found that PL-L2 was positively correlated with the strength of FC between the left posterior STG and the precuneus during L2 switching, suggesting refinement of lexico-phonological representations and optimization of control processes. In this study, our results provided further evidence that higher PL-L2 was associated with stronger FC involving cerebellar and cortical regions. This pattern may reflect proficiency-dependent network refinement involving cerebello-cortical circuits, supporting more precise lexical-semantic processing in bilinguals.

4.5. Cerebellar FC and Usage-L2

We found a negative relationship between cerebello-cortical FC and the frequency of L2 use at home in bilinguals. Specifically, bilinguals who used L1 more frequently at home exhibited higher cerebellar FC between the lobules VI.R, VIIb.L, and bilateral VIIIa and the FFG.R. As discussed above, lobules VI and VIIIa are implicated in phonological and semantic processing, respectively. Additionally, lobule VIII is involved not only in language-related functions but also in executive functions (Stoodley & Schmahmann, 2009). The FFG.R has also been implicated in language processing, particularly in the visual recognition of written words. This region is more sensitive to the visual appearance of words rather than their intrinsic linguistic information (Dehaene et al., 2001, 2004; Qu et al., 2019). It responds to visual features such as letter case but does not exhibit sensitivity to phonological or semantic information. In the context of bilingualism, the FFG.R appears to be more engaged in processing the L1. (Giraud & Truy, 2002; Li et al., 2021; Mei et al., 2015; Suh et al., 2007). For instance, Suh et al. (2007) found that Korean-English bilinguals showed greater activation in the FFG.R during L1 processing. Additionally, a meta-analysis by Li et al. (2021) confirmed that the FFG.R consistently activates in response to L1 reading. These findings suggest that the FFG.R may play a role in processing familiar orthographic forms, contributing to the automatic and efficient recognition of L1 words. In the current study, we found that higher cerebellar FC involving L1 processing was related to the increased frequency of L1 usage in bilinguals, which may reflect more efficient or automatized processing of L1-related visual and linguistic information. Furthermore, the negative association between cerebello-cortical FC and L2 home usage suggested that reduced L1 exposure might lead to weaker connectivity patterns, potentially reflecting a shift in neural engagement as bilinguals allocate more cognitive resources to L2 processing at home.

Cerebellar FC between the lobule IX.R and the INS.L was positively correlated with Usage-L2 in social situations. A previous study has shown that the insula plays a crucial role in language conflict monitoring in bilinguals (Teubner-Rhodes et al., 2019). Bilinguals have been found to exhibit greater activation of the INS during conflict detection tasks. This region is involved in the controlled retrieval of semantic information when external cues are insufficient to support retrieval (Badre et al., 2005). It is engaged in tasks requiring the maintenance and retrieval of task goals, especially when dealing with multidimensional stimuli associated with multiple response rules. Moreover, bilinguals tend to rely more on the neural resources involved in language switching, such as the left ventrolateral prefrontal cortex (VLPFC)/insula, to detect conflict accurately. This increased activation in the left VLPFC/insula during conflict monitoring tasks may indicate that bilinguals use top-down control to retrieve goal-relevant information, leading to improved accuracy following congruent trials and potentially slower response time. We observed higher functional connectivity between the IX.R and the INS.L, which was associated with increased Usage-L2 in social settings. This may be because, as L2 usage increases in dynamic, real-world social interactions, bilinguals enhance their conflict monitoring of different languages. Our result was in line with previous findings that increased Usage-L2 in social settings is associated with heightened demands for language control (DeLuca et al., 2019).

5. Limitations and future directions

It should be noted that this study had several limiting factors. First, we only focused on static but not dynamic cerebellar FC induced by bilingual experiences. Recent studies showed that significant difference in functional network dynamics between early and late bilinguals suggested that early language experiences may affect the dynamic reorganization of neural networks in bilinguals (Liu et al., 2020; Sheng et al., 2023). However, previous studies have demonstrated the need for more than 10 minutes to acquire resting-state fMRI data when the data was applied in dynamic analysis (Hindriks et al., 2016; Tomasi et al., 2017). Given the limitation of the current data, we cannot analyze the cerebellar network dynamics in this study. Future studies should lengthen the scanning time and then investigate the effect of bilingualism on the dynamic properties of the cerebellar network. Second, we investigated the effect of bilingual experiences on cerebellar FC using multiple regression analysis, without considering the non-linear nature of neuroplasticity in the brain. The DRM suggests that bilingualism-induced neuroplasticity follows a dynamic trajectory, with structural adaptions occurring at different stages of L2 learning. Recent studies have increasingly applied non-linear analyses to examine how bilingual experiences shape brain structural changes (DeLuca & Voits, 2022; DeLuca et al., 2024; Korenar et al., 2023b). These findings highlight the importance of capturing non-linear developmental patterns in the bilingual brain. Future studies should investigate whether the functional neuroplasticity of the cerebellum follows similar non-linear trajectories in bilinguals. Last but not least, we examined differences in cerebellar functional neuroplasticity between monolinguals and bilinguals, which may involve an inherent limitation associated with this comparative framework (Dash et al., 2022; De Houwer, 2023; Rothman et al., 2023). This framework risks reinforcing biases regarding monolinguals and bilinguals, potentially implying that monolingualism constitutes a normative baseline or that bilinguals are expected to demonstrate equal proficiency in both languages. Such assumptions overlook the multidimensional nature of bilingualism, which emerges from complex and dynamic interactions between language acquisition history, proficiency levels, usage patterns and sociocultural contexts. Future studies should adopt more comprehensive frameworks, such as the network model of bilingualism (Kałamała et al., 2023), to investigate how language background and bilingual experience-related factors influence cerebellar functional neuroplasticity during L2 acquisition (i.e., the transition from monolingualism to bilingualism).

6. Conclusion

In this study, we examined the effect of bilingualism on functional neuroplasticity of the cerebellum. We found that monolinguals exhibited higher FC between cerebellar regions and temporal lobe regions. AoA-L2 modulated cerebello-cortical FC, particularly involving the VI, Crus I, VIII and IX, along with relevant cortical language regions. Also, increased AoA-L2 was related to increased cerebellar FC between bilateral IX and subcortical regions (caudate and thalamus). This pattern suggested that late bilinguals may rely more on cerebellar and subcortical regions to support L2 learning. Immersion-L2 was negatively related to cerebellar FC, which may reflect that with increased immersional duration of L2, the bilingual brain reorganizes the neural circuits of the cerebellum to increase language processing efficiency. Higher PL-L2 in bilinguals was associated with stronger cerebellar FC, supporting more precise L2 processing. Increased Usage-L2 at home was associated with decreased cerebellar FC between the IX and the FFG, while increased cerebellar involving the IX and INS was observed in bilinguals who use L2 frequently in social settings. Our results highlighted the potential impact of bilingualism on the cerebello-cortical and cerebello-subcortical neural pathways and suggested that AoA-L2, Immersion-L2, PL-L2 and Usage-L2 shape the cerebellar FC in different ways. These findings improved our understanding of how bilingual experiences influence the functional neuroplasticity of the cerebellum.

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Data availability statement. The data comes from these open datasets: (1) "The Reading Brain Project L1 Adults" dataset (https://openneuro.org/datasets/ds003974/versions/3.0.0); (2) "The Reading Brain Project L2 Adults" dataset, (https://openneuro.org/datasets/ds003988/versions/1.0.0); (3) "Bilingualism and the Brain" dataset (https://openneuro.org/datasets/ds001796/versions/1.3.0). The corresponding processed MRI images data and analysis codes related to this publication will be available upon request with a legitimate reason.

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Competing interests. The authors declare none.

References

Abutalebi, J., & **Green, D. W.** (2016). Neuroimaging of language control in bilinguals: Neural adaptation and reserve. *Bilingualism: Language and Cognition*, **19**(4), 689–698.

Amoruso, L., **García, A. M.**, **Pusil, S.**, **Timofeeva, P.**, **Quiñones, I.**, & **Carreiras, M.** (2024). Decoding bilingualism from resting-state oscillatory network organization. *Annals of the New York Academy of Sciences*, **1534**(1), 106–117.

Amoruso, L., **Pusil, S.**, **García, A. M.**, & **Ibañez, A.** (2022). Decoding motor expertise from fine-tuned oscillatory network organization. *Human Brain Mapping*, **43**(9), 2817–2832.

Badre, D., **Poldrack, R. A.**, **Paré-Blagoev, E. J.**, **Insler, R. Z.**, & **Wagner, A. D.** (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*, **47**(6), 907–918.

Bennett, C. M., **Wolford, G. L.**, & **Miller, M. B.** (2009). The principled control of false positives in neuroimaging. *Social Cognitive and Affective Neuroscience*, **4**(4), 417–422.

Berken, J. A., **Chai, X.**, **Chen, J.-K.**, **Gracco, V. L.**, & **Klein, D.** (2016). Effects of early and late bilingualism on resting-state functional connectivity. *Journal of Neuroscience*, **36**(4), 1165–1172.

Binder, J. R., **Desai, R. H.**, **Graves, W. W.**, & **Conant, L. L.** (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, **19**(12), 2767–2796.

Brice, A. E., **Salnaitis, C.**, & **MacPherson, M. K.** (2023). Neural activation in bilinguals and monolinguals using a word identification task. *Language*, **8**(3), 216.

Bushara, K. O., **Wheat, J. M.**, **Khan, A.**, **Mock, B. J.**, **Turski, P. A.**, **Sorenson, J.**, & **Brooks, B. R.** (2001). Multiple tactile maps in the human cerebellum. *Neuroreport*, **12**(11), 2483–2486.

Cao, C., **Zhang, D.**, & **Liu, W.** (2022). Abnormal topological parameters in the default mode network in patients with impaired cognition undergoing maintenance hemodialysis. *Frontiers in Neurology*, **13**, 951302.

Chen, S. A., & **Desmond, J. E.** (2005). Temporal dynamics of cerebro-cerebellar network recruitment during a cognitive task. *Neuropsychologia*, **43**(9), 1227–1237.

D'Mello, A. M., **Centanni, T. M.**, **Gabrieli, J. D.**, & **Christodoulou, J. A.** (2020). Cerebellar contributions to rapid semantic processing in reading. *Brain and Language*, **208**, 104828.

D'Mello, A. M., **Moore, D. M.**, **Crocetti, D.**, **Mostofsky, S. H.**, & **Stoodley, C. J.** (2016). Cerebellar gray matter differentiates children with early language delay in autism. *Autism Research*, **9**(11), 1191–1204.

Danylkiv, A., & **Krafnick, A. J.** (2020). A meta-analysis of gray matter differences between bilinguals and monolinguals. *Frontiers in Human Neuroscience*, **14**, 146.

Dash, T., **Joanette, Y.**, & **Ansaldo, A. I.** (2022). Multifactorial approaches to study bilingualism in the aging population: Past, present, future. *Frontiers in Psychology*, **13**, 917959.

De Houwer, A. (2023). The danger of bilingual–monolingual comparisons in applied psycholinguistic research. *Applied PsychoLinguistics*, **44**(3), 343–357.

De Smet, H. J., **Paquier, P.**, **Verhoeven, J.**, & **Mariën, P.** (2013). The cerebellum: Its role in language and related cognitive and affective functions. *Brain and Language*, **127**(3), 334–342.

Dehaene, S., **Jobert, A.**, **Naccache, L.**, **Ciuciu, P.**, **Poline, J.-B.**, **Le Bihan, D.**, & **Cohen, L.** (2004). Letter binding and invariant recognition of masked words: Behavioral and neuroimaging evidence. *Psychological Science*, **15**(5), 307–313.

Dehaene, S., **Naccache, L.**, **Cohen, L.**, **Bihan, D. L.**, **Mangin, J.-F.**, **Poline, J.-B.**, & **Rivière, D.** (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Neuroscience*, **4**(7), 752–758.

DeLuca, V., **Rothman, J.**, **Bialystok, E.**, & **Pliatsikas, C.** (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, **116**(15), 7565–7574.

DeLuca, V., **Rothman, J.**, **Bialystok, E.**, & **Pliatsikas, C.** (2020a). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage*, **204**, 116222.

DeLuca, V., **Rothman, J.**, & **Pliatsikas, C.** (2019). Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Bilingualism: Language and Cognition*, **22**(5), 1160–1175.

DeLuca, V., **Segaert, K.**, **Mazaheri, A.**, & **Krott, A.** (2020b). Understanding bilingual brain function and structure changes? U bet! A unified bilingual experience trajectory model. *Journal of Neurolinguistics*, **56**, 100930.

DeLuca, V., & **Voits, T.** (2022). Bilingual experience affects white matter integrity across the lifespan. *Neuropsychologia*, **169**, 108191.

DeLuca, V., **Voits, T.**, **Ni, J.**, **Carter, F.**, **Rahman, F.**, **Mazaheri, A.**, … **Segaert, K.** (2024). Mapping individual aspects of bilingual experience to adaptations in brain structure. *Cerebral Cortex*, **34**(2), bhae029.

Desmond, J. E., **Gabrieli, J. D.**, **Wagner, A. D.**, **Ginier, B. L.**, & **Glover, G. H.** (1997). Lobular patterns of cerebellar activation in verbal working-memory and finger-tapping tasks as revealed by functional MRI. *Journal of Neuroscience*, **17**(24), 9675–9685.

Diedrichsen, J., **Balsters, J. H.**, **Flavell, J.**, **Cussans, E.**, & **Ramnani, N.** (2009). A probabilistic MR atlas of the human cerebellum. *NeuroImage*, **46**(1), 39–46.

Diedrichsen, J., **King, M.**, **Hernandez-Castillo, C.**, **Sereno, M.**, & **Ivry, R. B.** (2019). Universal transform or multiple functionality? Understanding the contribution of the human cerebellum across task domains. *Neuron*, **102**(5), 918–928.

Du, J., **Rolls, E. T.**, **Cheng, W.**, **Li, Y.**, **Gong, W.**, **Qiu, J.**, & **Feng, J.** (2020). Functional connectivity of the orbitofrontal cortex, anterior cingulate cortex, and inferior frontal gyrus in humans. *Cortex*, **123**, 185–199.

Follmer, D. J., **Fang, S.-Y.**, **Clariana, R. B.**, **Meyer, B. J.**, & **Li, P.** (2018). What predicts adult readers' understanding of STEM texts? *Reading and Writing*, **31**, 185–214.

Frings, M., **Dimitrova, A.**, **Schorn, C. F.**, **Elles, H.-G.**, **Hein-Kropp, C.**, **Gizewski, E. R.**, & **Timmann, D.** (2006). Cerebellar involvement in verb generation: An fMRI study. *Neuroscience Letters*, **409**(1), 19–23.

Giraud, A. L., & **Truy, E.** (2002). The contribution of visual areas to speech comprehension: A PET study in cochlear implants patients and normal-hearing subjects. *Neuropsychologia*, **40**(9), 1562–1569.

Gold, C. E. (2018). *Exploring the resting state neural activity of monolinguals and late and early bilinguals*. Brigham Young University.

Grahn, J. A., **Parkinson, J. A.**, & **Owen, A. M.** (2008). The cognitive functions of the caudate nucleus. *Progress in Neurobiology*, **86**(3), 141–155.

Grant, A., & **Li, P.** (2019). Proficiency affects intra-and inter-regional patterns of language control in second language processing. *Language, Cognition and Neuroscience*, **34**(6), 787–802.

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

Hindriks, R., **Adhikari, M. H.**, **Murayama, Y.**, **Ganzetti, M.**, **Mantini, D.**, **Logothetis, N. K.**, & **Deco, G.** (2016). Can sliding-window correlations reveal dynamic functional connectivity in resting-state fMRI? *NeuroImage*, **127**, 242–256.

Jiang, X., **Ma, X.**, **Sanford, R.**, & **Li, X.** (2024). Adapting to changes in communication: The orbitofrontal cortex in language and speech processing. *Brain Sciences*, **14**(3), 264.

Jin, Y., **Fan, X.**, **Xu, X.**, **Pan, N.**, **Jing, J.**, **Song, X.**, & **Li, X.** (2023). The differences in structure and function of the cerebellum between Cantonese-Mandarin bilinguals and mandarin monolinguals: A multi-model MRI study. *The Cerebellum*, **22**(4), 628–639.

Johnston, J. (1984). *Econometric methods*. McGraw-Hill Education.

Kałamała, P., **Chuderski, A.**, **Szewczyk, J.**, **Senderecka, M.**, & **Wodniecka, Z.** (2023). Bilingualism caught in a net: A new approach to understanding the complexity of bilingual experience. *Journal of Experimental Psychology: General*, **152**(1), 157.

Kim, J., **Criaud, M.**, **Cho, S. S.**, **Díez-Cirarda, M.**, **Mihaescu, A.**, **Coakeley, S.**, & **Strafella, A. P.** (2017). Abnormal intrinsic brain functional network dynamics in Parkinson's disease. *Brain*, **140**(11), 2955–2967.

Koppelmans, V., **Hoogendam, Y. Y.**, **Hirsiger, S.**, **Mérillat, S.**, **Jäncke, L.**, & **Seidler, R. D.** (2017). Regional cerebellar volumetric correlates of manual motor and cognitive function. *Brain Structure & Function*, **222**, 1929–1944.

Korenar, M., **Treffers-Daller, J.**, & **Pliatsikas, C.** (2023a). Brain structure adapts dynamically to highly demanding bilingual experiences: Insights from interpreters and translators. *Ampersand*, **11**, 100148.

Korenar, M., **Treffers-Daller, J.**, & **Pliatsikas, C.** (2023b). Dynamic effects of bilingualism on brain structure map onto general principles of experience-based neuroplasticity. *Scientific Reports*, **13**(1), 3428.

Kovelman, I., **Baker, S. A.**, & **Petitto, L.-A.** (2008). Bilingual and monolingual brains compared: A functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature of bilingualism". *Journal of Cognitive Neuroscience*, **20**(1), 153–169.

LeBel, A., & **D'Mello, A. M.** (2023). A seat at the (language) table: Incorporating the cerebellum into frameworks for language processing. *Current Opinion in Behavioral Sciences*, **53**, 101310.

Li, H., **Kepinska, O.**, **Caballero, J. N.**, **Zekelman, L.**, **Marks, R. A.**, **Uchikoshi, Y.**, & **Hoeft, F.** (2021). Decoding the role of the cerebellum in the early stages of reading acquisition. *Cortex*, **141**, 262–279.

Li, H., **Zhang, J.**, & **Ding, G.** (2021). Reading across writing systems: A meta-analysis of the neural correlates for first and second language reading. *Bilingualism: Language and Cognition*, **24**(3), 537–548.

Li, L., **Abutalebi, J.**, **Zou, L.**, **Yan, X.**, **Liu, L.**, **Feng, X.**, … **Ding, G.** (2015). Bilingualism alters brain functional connectivity between "control" regions and "language" regions: Evidence from bimodal bilinguals. *Neuropsychologia*, **71**, 236–247.

Li, P., & **Clariana, R. B.** (2019). Reading comprehension in L1 and L2: An integrative approach. *Journal of Neurolinguistics*, **50**, 94–105.

Lieberman, M. D., & **Cunningham, W. A.** (2009). Type I and type II error concerns in fMRI research: Re-balancing the scale. *Social Cognitive and Affective Neuroscience*, **4**(4), 423–428.

Linck, J. A., **Kroll, J. F.**, & **Sunderman, G.** (2009). Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second-language learning. *Psychological Science*, **20**(12), 1507–1515.

Liu, C., **Jiao, L.**, **Li, Z.**, **Timmer, K.**, & **Wang, R.** (2021). Language control network adapts to second language learning: A longitudinal rs-fMRI study. *Neuropsychologia*, **150**, 107688.

Liu, X., **Tu, L.**, **Chen, X.**, **Wang, J.**, **Li, M.**, **Lu, Z.**, & **Huang, R.** (2021). Effect of AoA-L2 on L1 and L2 networks in early and late bilinguals. *International Journal of Bilingualism*, **25**(6), 1616–1634.

Liu, X., **Tu, L.**, **Chen, X.**, **Zhong, M.**, **Niu, M.**, **Zhao, L.**, & **Huang, R.** (2020). Dynamic language network in early and late Cantonese–mandarin bilinguals. *Frontiers in Psychology*, **11**, 1189.

Liu, X., **Tu, L.**, **Wang, J.**, **Jiang, B.**, **Gao, W.**, **Pan, X.**, & **Huang, R.** (2017). Onset age of L2 acquisition influences language network in early and late Cantonese-mandarin bilinguals. *Brain and Language*, **174**, 16–28.

Luk, G., **Green, D. W.**, **Abutalebi, J.**, & **Grady, C.** (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, **27**(10), 1479–1488.

Marian, V., **Chabal, S.**, **Bartolotti, J.**, **Bradley, K.**, & **Hernandez, A. E.** (2014). Differential recruitment of executive control regions during phonological competition in monolinguals and bilinguals. *Brain and Language*, **139**, 108–117.

Mariën, P., **Ackermann, H.**, **Adamaszek, M.**, **Barwood, C. H.**, **Beaton, A.**, **Desmond, J.**, & **Ziegler, W.** (2014). Consensus paper: Language and the cerebellum: An ongoing enigma. *The Cerebellum*, **13**, 386–410.

Mariën, P., **van Dun, K.**, **Van Dormael, J.**, **Vandenborre, D.**, **Keulen, S.**, **Manto, M.**, & **Abutalebi, J.** (2017). Cerebellar induced differential polyglot aphasia: A neurolinguistic and fMRI study. *Brain and Language*, **175**, 18–28.

Marin-Marin, L., **Costumero, V.**, **Ávila, C.**, & **Pliatsikas, C.** (2022). Dynamic effects of immersive bilingualism on cortical and subcortical grey matter volumes. *Frontiers in Psychology*, **13**, 886222.

Martin, C. D., **Strijkers, K.**, **Santesteban, M.**, **Escera, C.**, **Hartsuiker, R. J.**, & **Costa, A.** (2013). The impact of early bilingualism on controlling a language learned late: An ERP study. *Frontiers in Psychology*, **4**, 815.

McDermott, K. B., **Petersen, S. E.**, **Watson, J. M.**, & **Ojemann, J. G.** (2003). A procedure for identifying regions preferentially activated by attention to semantic and phonological relations using functional magnetic resonance imaging. *Neuropsychologia*, **41**(3), 293–303.

Mei, L., **Xue, G.**, **Lu, Z.-L.**, **Chen, C.**, **Wei, M.**, **He, Q.**, & **Dong, Q.** (2015). Long-term experience with Chinese language shapes the fusiform asymmetry of English reading. *NeuroImage*, **110**, 3–10.

Mondt, K., **Balériaux, D.**, **Metens, T.**, **Paquier, P.**, **Van de Craen, P.**, **Van den Noort, M.**, & **Denolin, V.** (2009). An fMRI study of level of proficiency as a predictor of neurocognitive convergence for L1/L2 during a lexicosemantic task in a paediatric population. *Second Language Research*, **25**(1), 107–134.

Moore, D. M., **D'Mello, A. M.**, **McGrath, L. M.**, & **Stoodley, C. J.** (2017). The developmental relationship between specific cognitive domains and grey matter in the cerebellum. *Developmental Cognitive Neuroscience*, **24**, 1–11.

Mouthon, M., **Khateb, A.**, **Lazeyras, F.**, **Pegna, A. J.**, **Lee-Jahnke, H.**, **Lehr, C.**, & **Annoni, J.-M.** (2020). Second-language proficiency modulates the brain language control network in bilingual translators: An event-related fMRI study. *Bilingualism: Language and Cognition*, **23**(2), 251–264.

Nguyen, M. V., **Xu, Y.**, **Vaughn, K. A.**, & **Hernandez, A. E.** (2024). Subcortical and cerebellar volume differences in bilingual and monolingual children: An ABCD study. *Developmental Cognitive Neuroscience*, **65**, 101334.

Palomar-García, M.-Á., **Bueichekú, E.**, **Ávila, C.**, **Sanjuán, A.**, **Strijkers, K.**, **Ventura-Campos, N.**, & **Costa, A.** (2015). Do bilinguals show neural differences with monolinguals when processing their native language? *Brain and Language*, **142**, 36–44.

Pillai, J. J., **Allison, J. D.**, **Sethuraman, S.**, **Araque, J. M.**, **Thiruvaiyaru, D.**, **Ison, C. B.**, & **Lavin, T.** (2004). Functional MR imaging study of language-related differences in bilingual cerebellar activation. *American Journal of Neuroradiology*, **25**(4), 523–532.

Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The dynamic restructuring model. *Bilingualism: Language and Cognition*, **23**(2), 459–471.

Pliatsikas, C., **Johnstone, T.**, & **Marinis, T.** (2014). Grey matter volume in the cerebellum is related to the processing of grammatical rules in a second language: A structural voxel-based morphometry study. *The Cerebellum*, **13**, 55–63.

Price, C. J. (2010). The anatomy of language: A review of 100 fMRI studies published in 2009. *Annals of the New York Academy of Sciences*, **1191**(1), 62–88.

Qu, J., **Zhang, L.**, **Chen, C.**, **Xie, P.**, **Li, H.**, **Liu, X.**, & **Mei, L.** (2019). Cross-language pattern similarity in the bilateral fusiform cortex is associated with reading proficiency in second language. *Neuroscience*, **410**, 254–263.

Rolls, E. T., **Huang, C.-C.**, **Lin, C.-P.**, **Feng, J.**, & **Joliot, M.** (2020). Automated anatomical labelling atlas 3. *NeuroImage*, **206**, 116189.

Rothman, J., **Bayram, F.**, **DeLuca, V.**, **Di Pisa, G.**, **Duñabeitia, J. A.**, **Gharibi, K.**, & **Kupisch, T.** (2023). Monolingual comparative normativity in bilingualism research is out of "control": Arguments and alternatives. *Applied PsychoLinguistics*, **44**(3), 316–329.

Schremm, A., **Novén, M.**, **Horne, M.**, **Söderström, P.**, **van Westen, D.**, & **Roll, M.** (2018). Cortical thickness of planum temporale and pars opercularis in native language tone processing. *Brain and Language*, **176**, 42–47.

Schug, A. K., **Brignoni-Pérez, E.**, **Jamal, N. I.**, & **Eden, G. F.** (2022). Gray matter volume differences between early bilinguals and monolinguals: A study of children and adults. *Human Brain Mapping*, **43**(16), 4817–4834.

Sheng, Y., **Yang, S.**, **Rao, J.**, **Zhang, Q.**, **Li, J.**, **Wang, D.**, & **Zheng, W.** (2023). Age of bilingual onset shapes the dynamics of functional connectivity and laterality in the resting-state. *Brain Sciences*, **13**(9), 1231.

Smallwood, J., **Bernhardt, B. C.**, **Leech, R.**, **Bzdok, D.**, **Jefferies, E.**, & **Margulies, D. S.** (2021). The default mode network in cognition: A topographical perspective. *Nature Reviews Neuroscience*, **22**(8), 503–513.

Stoodley, C. J., & **Schmahmann, J. D.** (2009). Functional topography in the human cerebellum: A meta-analysis of neuroimaging studies. *NeuroImage*, **44**(2), 489–501.

Suh, S., **Yoon, H. W.**, **Lee, S.**, **Chung, J.-Y.**, **Cho, Z.-H.**, & **Park, H.** (2007). Effects of syntactic complexity in L1 and L2; an fMRI study of Korean–English bilinguals. *Brain Research*, **1136**, 178–189.

Sulpizio, S., **Del Maschio, N.**, **Del Mauro, G.**, **Fedeli, D.**, & **Abutalebi, J.** (2020a). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage*, **205**, 116306.

Sulpizio, S., **Del Maschio, N.**, **Fedeli, D.**, & **Abutalebi, J.** (2020b). Bilingual language processing: A meta-analysis of functional neuroimaging studies. *Neuroscience & Biobehavioral Reviews*, **108**, 834–853.

Tan, L. H., **Laird, A. R.**, **Li, K.**, & **Fox, P. T.** (2005). Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: A meta-analysis. *Human Brain Mapping*, **25**(1), 83–91.

Teubner-Rhodes, S., **Bolger, D. J.**, & **Novick, J. M.** (2019). Conflict monitoring and detection in the bilingual brain. *Bilingualism: Language and Cognition*, **22**(2), 228–252.

Tian, Y., **Margulies, D. S.**, **Breakspear, M.**, & **Zalesky, A.** (2020). Topographic organization of the human subcortex unveiled with functional connectivity gradients. *Nature Neuroscience*, **23**(11), 1421–1432.

Tomasi, D. G., **Shokri-Kojori, E.**, & **Volkow, N. D.** (2017). Temporal evolution of brain functional connectivity metrics: Could 7 min of rest be enough? *Cerebral Cortex*, **27**(8), 4153–4165.

Tu, L., **Wang, J.**, **Abutalebi, J.**, **Jiang, B.**, **Pan, X.**, **Li, M.**, & **Huang, R.** (2015). Language exposure induced neuroplasticity in the bilingual brain: A follow-up fMRI study. *Cortex*, **64**, 8–19.

Turker, S., **Kuhnke, P.**, **Eickhoff, S. B.**, **Caspers, S.**, & **Hartwigsen, G.** (2023). Cortical, subcortical, and cerebellar contributions to language processing: A meta-analytic review of 403 neuroimaging experiments. *Psychological Bulletin*, **149**, 11–12.

Vias, C., & **Dick, A. S.** (2017). Cerebellar contributions to language in typical and atypical development: A review. *Developmental Neuropsychology*, **42**(6), 404–421.

Wang, J., **Lu, M.**, **Fan, Y.**, **Wen, X.**, **Zhang, R.**, **Wang, B.**, & **Huang, R.** (2016). Exploring brain functional plasticity in world class gymnasts: A network analysis. *Brain Structure and Function*, **221**, 3503–3519.

Wang, J., **Wang, X.**, **Xia, M.**, **Liao, X.**, **Evans, A.**, & **He, Y.** (2015). GRETNA: A graph theoretical network analysis toolbox for imaging connectomics. *Frontiers in Human Neuroscience*, **9**, 386.

Wang, J., **Zuo, X.**, & **He, Y.** (2010). Graph-based network analysis of resting-state functional MRI. *Frontiers in Systems Neuroscience*, **4**, 1419.

Wang, R., **Ke, S.**, **Zhang, Q.**, **Zhou, K.**, **Li, P.**, & **Yang, J.** (2020). Functional and structural neuroplasticity associated with second language proficiency: An MRI study of Chinese-English bilinguals. *Journal of Neurolinguistics*, **56**, 100940.

Wu, C.-Y., **Ho, M.-H. R.**, & **Chen, S.-H. A.** (2012). A meta-analysis of fMRI studies on Chinese orthographic, phonological, and semantic processing. *NeuroImage*, **63**(1), 381–391.

Yi, H. G., **Leonard, M. K.**, & **Chang, E. F.** (2019). The encoding of speech sounds in the superior temporal gyrus. *Neuron*, **102**(6), 1096–1110.

Yuan, Q., **Li, H.**, **Du, B.**, **Dang, Q.**, **Chang, Q.**, **Zhang, Z.**, & **Guo, T.** (2023). The cerebellum and cognition: Further evidence for its role in language control. *Cerebral Cortex*, **33**(1), 35–49.

Yuan, Q., **Wu, J.**, **Zhang, M.**, **Zhang, Z.**, **Chen, M.**, **Ding, G.**, & **Guo, T.** (2021). Patterns and networks of language control in bilingual language production. *Brain Structure & Function*, **226**, 963–977.

Zhang, R., **Wang, J.**, **Lin, H.**, **Turk-Browne, N. B.**, & **Cai, Q.** (2023). Neural signatures of second language proficiency in narrative processing. *Cerebral Cortex*, **33**(13), 8477–8484.

Zhao, L., **Tu, L.**, **Zhang, M.**, **Liu, X.**, **Pan, X.**, **Wang, J.**, & **Huang, R.** (2023). The effects of second-language age of acquisition on brain structural networks: A DTI study of high-proficient bilinguals. *Journal of Neurolinguistics*, **68**, 101155.