



Language control network adapts to second language learning: A longitudinal rs-fMRI study

Cong Liu^{a,b}, Lu Jiao^a, Zilong Li^b, Kalinka Timmer^c, Ruiming Wang^{b,*}

^a Department of Psychology, Normal College & School of Teacher Education, Qingdao University, Qingdao, China

^b Key Laboratory of Brain, Cognition and Education Sciences, Ministry of Education, & Guangdong Provincial Key Laboratory of Mental Health and Cognitive Science, Center for Studies of Psychological Application, School of Psychology, South China Normal University, Guangzhou, China

^c Psychology of Language and Bilingualism Lab, Institute of Psychology, Jagiellonian University, Kraków, Poland

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ABSTRACT

The current longitudinal resting-state functional magnetic resonance imaging study examined changes in language control network after one year of L2 English classroom learning. A group of Chinese college freshmen majoring in English underwent two scans, one before (i.e., Session 1) and one after (i.e., Session 2) the one-year L2 courses. Learners' language control abilities were assessed via a behavioral language switching task. Our graph theory and functional connectivity analyses revealed that with increased exposure to the L2, nodal betweenness in language control areas, such as the dorsal anterior cingulate cortex (dACC), decreased and connectivity between dACC and pre-supplementary motor area (pre-SMA) increased. Critically, these neural changes were correlated with participants' behavioral performance on the language switching task. Taken together, these findings suggest that the language control network in resting brain could be modulated by long-term L2 learning in a naturalistic classroom setting, and that the dACC/pre-SMA complex appears to play a critical role in language control.

1. Introduction

Previous research has demonstrated that second language (L2) experience leads to functional and structural neural adaptations (Abutalebi et al., 2011; Li et al., 2014; Abutalebi and Green, 2016; Pliatsikas et al., 2017; Zou et al., 2012). However, so far only a few studies have focused on how L2 learning shapes resting-state connectivity. This is especially interesting for potential changes in the language control network, which is activated for bilinguals when switching between their languages. Hence, the current study adopted a longitudinal resting-state functional magnetic resonance imaging (rs-fMRI) approach to investigate how long-term classroom L2 learning over the course of one year modulated the resting-state connectivity of the language control network.

1.1. Bilingual language control

Bilingual language control refers to a set of cognitive abilities that allow bilinguals to minimize cross-language interference from the nontarget language when speaking in the intended language (for a

review, see Declerck and Philipp, 2015). To investigate the underlying mechanisms of language control, previous studies have employed language switching tasks (Liu et al., 2019; Meuter and Allport, 1999). In this task participants are asked to name digits or pictures in either their first language (L1) or second language (L2), based on specific cues. It is typically found that switching from one language to another (i.e., switch trials) yields longer reaction times (RTs) than repeating the same language in two subsequent trials (i.e., repetition trials). This so-called switch cost is a psychological index of language control (Meuter and Allport, 1999). Moreover, the switch cost is often asymmetrical (i.e., L2-L1 switch cost is larger than L1-L2 switch cost) for unbalanced bilinguals (Meuter and Allport, 1999; Philipp et al., 2007). This suggests that inhibitory control is involved to a greater degree when switching to the L1 than L2 (see Inhibitory Control Model in Green, 1998).

It has been argued that a network of cortical and subcortical brain areas is recruited during language control processes (Calabria et al., 2018; Abutalebi and Green, 2016). In a recent meta-analysis eight brain areas were identified as the neural correlates of bilingual cognitive control, including the left middle frontal gyrus, pre-supplementary motor area (pre-SMA), left inferior frontal gyrus, right precentral

* Corresponding author.

E-mail address: wangrm@scnu.edu.cn (R. Wang).

gyrus, left middle temporal gyrus, right superior temporal gyrus, and bilateral caudate nuclei (Luk et al., 2012). Moreover, the dorsal anterior cingulate cortex (dACC) has also been proposed to be involved in bilingual language control processing and is often considered to work in concert with the pre-SMA (e.g., Green and Abutalebi, 2013; Abutalebi and Green, 2016). Branzi et al. (2015) proposed that both brain areas (i.e., dACC/pre-SMA complex) acted as the supervisory attentional system. They are recruited during increased monitoring demands, such as language control in the weaker second language.

1.2. The modulation of language control network by L2 learning

At least two theories have suggested that language control could be modulated by L2 learning: the Adaptive Control Hypothesis (ACH) (Green and Abutalebi, 2013) and the Dynamic Restructuring Model (DRM) (Pliatsikas, 2020). The ACH proposes that bilingual language control mechanisms are not static but adapt depending on a bilinguals' pattern of language use and L2 learning experience (Green and Abutalebi, 2013; Abutalebi and Green, 2016; for a review see Wodniecka et al., 2020). Similarly, the DRM proposes that during the early exposure to a new language structural changes seem to occur in some brain regions related to language control (e.g., ACC, IFG, and MFG) (Pliatsikas, 2020). Thus, bilingual language control is dynamic and adjusts to the current language experience and demands in the environment.

In line with both theories, neural adaptations in areas related to language control have been observed in a number of structural neuroimaging studies (Legault et al., 2019; Martensson et al., 2012; Schlegel et al., 2012). For example, Abutalebi et al. (2011) found that increased grey matter density in the ACC correlated with better conflict monitoring. This was only the case for bilinguals and not in their monolingual counterparts. Similarly, Felton et al. (2017) showed that bilinguals had greater thickness in the right ACC compared to monolinguals. In addition to the above-mentioned cross-sectional studies, further evidence for neuroplasticity during L2 learning stems from longitudinal studies. In a voxel-based morphometry (VBM) study, Stein et al. (2012) observed increased grey matter density in the left inferior frontal gyrus after five months of L2 learning. This structural change correlated positively with L2 proficiency. More recently, Legault et al. (2019) found that English-Spanish language learners showed greater cortical thickness in the left ACC and right middle temporal gyrus (MTG) after four months of L2 learning. Notably, as the ACC plays a critical role in the widespread "bilingual language control" network (Abutalebi and Green, 2016), the structural evidence above suggests that language learning experience restructures cortical regions linked to language control.

Next to structural changes, functional changes have also been observed in recent years due to L2 learning and/or bilingual experiences (Barbeau et al., 2017; Stein et al., 2009). Although the literature of the effects of bilingualism on resting state connectivity remains remarkably limited, the first evidence indicates that L2 learning might modulate the language control network. For instance, Chai et al. (2016) indicated that resting-state functional connectivity between the ACC and left anterior insula/frontal operculum correlated with improvement of L2 lexical retrieval in spontaneous speech after 12 weeks of intensive language training. Moreover, Li et al. (2015) compared Chinese bimodal bilinguals to monolinguals on connectivity between language regions and language processing regions. They found a decreased connectivity between the ACC and the left STG for the bilingual group compared to monolinguals. More specifically, the degree of functional connectivity within the language control network at rest has been suggested to be shaped by age of L2 acquisition (Berken et al., 2016). However, these studies did not employ tasks typically used to assess bilingual language control (e.g., language-switching task) to specifically explore how L2 learning adjusts bilingual language control. Since neuroimaging data are difficult to be interpreted in the absence of behavioral data (García-Pentón et al., 2016; Paap et al., 2015), it remains unclear how language control network adapts to L2 learning. Therefore, we correlate

the brain connectivity data with behavioral data in the present study. In addition, given researchers' suggestion that an ecological approach to bilingualism research is important (Blanco-Elorrieta and Pykkänen, 2018; Beatty-Martínez and Dussias, 2019), the present study set out to examine the effects of naturalistic classroom L2 learning on resting-state networks related to language control over a period of one year.

1.3. The present study

In the present study, a cohort of Chinese college freshmen majoring in English was recruited and underwent two resting-state scans approximately one year apart during their L2-acquisition courses at university. During this year, the participants took various English courses, including those focused on spoken, written, and intensive reading proficiency. All courses were taught in an all-English learning environment. This immersive L2 classroom learning experience reflects a more real-life setting in which L2 acquisition is more naturalistic. This differs from previous literature in which they looked at traditional L2 learning with formal instruction. There the experimental setting was highly restricted with specific training tasks, such as phonological/semantic choice task (Li et al., 2019; Qu et al., 2017). Formal L2 learning remotely resembles the richness of real-life experiences, limiting our understanding of naturalistic cognitive phenomena. In addition, previous studies have revealed that bilingual language control mechanisms adapt depending on the specific type of bilingual/L2 learning experience during daily life, like the amount of switching between languages in daily life (Green and Abutalebi, 2013). For a review of the long-(real-life) and short-term impact (experimental) of dynamic experience on bilingual language control see Wodniecka et al. (2020). We hypothesized that L2 learning in a more naturalistic setting might have stronger effects, due to greater usage of the L2 and thereby also more language switching between L1 and L2. Hence, although previous studies have examined the effects of L2 learning on the language control network in highly restricted experimental settings, it's necessary to further investigate how L2 learning in a naturalistic classroom setting (with an improved ecological validity).

We conducted graph theory, ROI-to-ROI connectivity, and seed-to-voxel connectivity analyses. This was done to examine if L2 learning induced adaptations in resting-state brain activity. While traditional functional connectivity analyses (i.e., ROI-to-ROI connectivity and seed-to-voxel connectivity analyses) provide a single metric of connectivity for each pair of regions within a particular network (in lower-level), the graph theory analysis allows us to visualize the overall connectivity pattern across brain regions. Graph-theory analysis also enables quantitatively characterizing the global organizational mechanism underlying the network (in higher-level; Medaglia, 2017). In addition, it gives insight into the topological reconfiguration of the brain network in response to task modulation (Wang et al., 2010). Specifically, it enables the characterization of the human brain as a highly efficient large-scale network consisting of nodes (i.e., brain regions) and edges (i.e., connections between the regions). This provides both *global metrics* to define the graph properties characterizing the global-level network organization and *regional metrics* to define the graph properties of particular brain region (node). The *global network properties* include Small-worldness (σ), global efficiency (E_{glob}), and local efficiency (E_{loc}). A small-world network is defined as a network that is more clustered than a random network. Yet, it has approximately the same characteristic path length (i.e., average of shortest path length) as a random network (Watts and Strogatz, 1998). E_{glob} measures how easily information can be exchanged throughout the network, providing information on the communication efficiency of the network as a whole. E_{loc} measures how efficient communication is among the neighboring nodes and is often interpreted as the local information processing capacity of a network. The *regional nodal properties* included nodal efficiency (E_{nodal}), nodal degree (D_{nodal}) and nodal betweenness (B_{nodal}) (Liu et al., 2017). E_{nodal} is defined as the shortest path length between a given node and other

nodes in the network. D_{nodal} is defined as the sum of the edges connected to one node within a network. E_{nodal} is defined as the fraction of the shortest paths between any pair of nodes that travel through the node.

In recent years, graph theory analysis has been widely used to evaluate the neural activity alterations in various diseases (Weizman et al., 2018; Zhang et al., 2019). However, it has only rarely been used in the field of L2 learning and bilingualism. The current study is one of the first to apply the graph theory analysis to reveal potential higher-level topological reconfiguration of the language control network induced by L2 learning. Next, ROI-to-ROI connectivity and seed-to-voxel connectivity analyses were employed to reveal potential alterations in lower-level functional organization. Both analyses enabled us to capture the full picture of how L2 learning leads to potential adaptations in resting-state brain activity.

1.4. Predictions

According to the ACH and DRM (Green and Abutalebi, 2013; Pliatsikas, 2020), we hypothesized that classroom L2 learning over the course of one year could shape the language control network. Specifically, for the graph theory analysis, both global and regional network properties of the language control network were expected to change after L2 language learning. This idea is supported by changes in these topological properties have been observed in individuals who learned a sign language (Liu et al., 2017). Similarly, for the functional connectivity analyses, previous studies provide support that L2 learning/bilingual experience could potentially improve functional connectivity strength (i.e., larger correlations coefficients) within language control areas (see Kang et al., 2017; Liu, de Bruin, Jiao, Li & Wang, submitted). We predicted that the functional connectivity between some key language control brain areas, such as the dACC/pre-SMA complex, would strengthen. It is important to note that we did not aim to directly examine the claims of the ACH or DRM in the present study. However, both theories gave us insights into the predictions and better theoretical understanding of the findings.

To further confirm the absence/presence of a direct link between resting-state connectivity and language control we used language switch cost (i.e., L2-L1 switch cost and L1-L2 switch cost) as a measurement of bilingual language control. We assessed whether neural changes in the bilingual language control network correlated with changes in language switch cost after L2 learning. Previous studies have already indicated that language control brain regions (e.g., bilateral frontal cortices and pre-SMA/ACC) were activated during forward switching (from L1 to L2), but not during backward switching (from L2 to L1) (Wang et al., 2007; Branzi et al., 2015) for the second language learners (i.e., non-proficient bilinguals). Therefore, we predict to find that neural changes in the bilingual language control network would mainly be correlated with L1-L2 switch cost, but not L2-L1 switch cost.

2. Methods

2.1. Participants

Twenty-five college freshmen, who are majoring in English, were recruited from the school of foreign studies in South China Normal University for this study. Exclusion criteria for participation included language or hearing impairment, history of traumatic brain injury, conditions incompatible with magnetic resonance imaging, and left handedness. From the twenty-five participants, three were excluded due to not having participated in the post-test session (i.e., Session 2) and two participants were excluded due to poor imaging quality. This left a total of 20 participants (18 females, mean age: 18.52 years, SD: 0.68, range: 17–20) in the analysis. The study was approved by the Research Ethics Board of South China Normal University, and participants gave written informed consent before the experiment.

All participants were living in China since birth and never abroad in

an English-speaking country more than three months. They had started learning English on average at 8 years of age (SD = 3.0, range: 3–13) and took the same English courses in their first year of university. None of them study in English-speaking countries or use English at home. Reported English use in daily life was 21% at Session 1 and 28% at Session 2. Self-assessed proficiency in both languages was rated on a scale of 1–7 (1 = not proficiency, 7 = very proficiency). A paired samples *t*-test showed that the participants were unbalanced Mandarin Chinese–English bilinguals with higher proficiency in Chinese than English ($p < 0.001$). Moreover, another paired-samples *t*-test revealed that the self-rated proficiency scores in English improved significantly after one year of L2 learning in a classroom setting ($t(20) = -3.327, p < 0.01$). See Table 1 for the language background information of the participants. In addition, participants completed the Oxford Placement Test (OPT) at Session 2 as an objective measure of English proficiency. The OPT contains 25 multiple choice questions and a cloze test. The maximum score is 50 with higher scores indicating greater English proficiency.

2.2. Stimuli and experimental design

The experiment consisted of two sessions: the first at the first semester of university (i.e., Session 1) and the second at the third semester (i.e., Session 2). Both sessions took place in October and November, with approximately one year in between the testing sessions. In both sessions, participants completed a self-rated language and a demographic questionnaire to assess their (language) background and proficiency. In addition, they underwent an fMRI scan composed of a non-task resting state, after which they performed the language switching task outside the MRI scanner to measure their language control abilities.

For the language switching task, sixteen black-and-white line drawings were selected from the database of Zhang and Yang (2003), of which four pictures were used during the practice phase. Attributes such as familiarity, visual complexity, and image agreement are matched according to Chinese and English norm data from Snodgrass and Vanderwart (1980) and Zhang and Yang (2003). Before the language switching experiment, participants were familiarized with the pictures and their corresponding names in both Chinese and English. They named all pictures until they could do so correctly. Then they completed one practice session of the switching task with 12 trials.

The language switching task included two blocks, each containing 48 switch trials and 48 non-switch trials, which were presented in a pseudo-randomized manner. Each trial began with both a fixation cross and a Chinese or American flag for 500 ms. Next, a picture was presented for 1500 ms, while the fixation and flag stayed on the screen. Participants were instructed to name each picture in the language indicated by the Chinese or American flag as quickly and accurately as possible. The Chinese flag indicated that the picture had to be named in Chinese while the American flag indicated it had to be named in English. Then a fixation cross was presented as a jittered inter-stimulus-interval (ISI) between 2000 ms and 5500 ms (in steps of 500 ms). See Fig. 1 for an example of the trial sequence. The jittered ISI is used here because this task was also conducted in the MRI scanner, but without verbal response data collection due to technical limitations. As the findings for the task-related MRI are reported in another paper (Liu et al., submitted), we do not focus on them here. The timing and order of trial presentation within

Table 1

Means (and SDs) of language proficiency as well as percentages of English use in daily life.

	Session 1	Session 2
Percentage of English use in daily life (%)	21 (15)	28 (11)
Self-rated proficiency score in Chinese	6.12 (0.91)	5.95 (0.55)
Self-rated proficiency score in English **	4.31 (0.68)	4.75 (0.60)
OPT score		41.25 (2.80)

** $p < 0.01$.

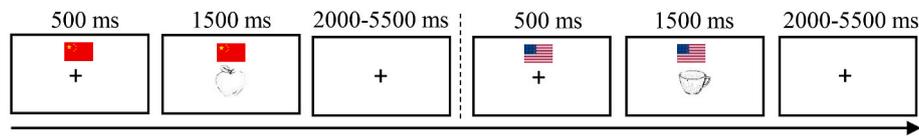


Fig. 1. Procedure of the language switching task.

each block were optimized for estimation efficiency using optseq2 (<http://surfer.nmr.mgh.harvard.edu/optseq/>).

2.3. fMRI data acquisition

All participants were scanned with a 3T Siemens Trio scanner, which includes a 12-channel phase array head coil, at South China Normal University. Resting-state fMRI images were acquired using T2-weighted gradient-echo planner imaging (EPI) sequence (TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 204 × 204 mm², matrix = 64 × 64, slice thickness = 3.5 mm, gap = 0.5 mm, voxel size = 3 × 3 × 3.5 mm³, acquisition time = 8:06 min). During the scanning, participants were instructed to stay still and keep their eyes closed without falling asleep. In addition, a T1-weighted structural image was acquired for each participant using the MPRAGE sequence (TR = 1900 ms, TE = 2.52 ms, flip angle = 9°, FOV = 256 × 256 mm², matrix = 204 × 204, slice thickness = 1 mm, voxel size 1 × 1 × 1 mm³, acquisition time = 4:26 min).

2.4. Data preprocessing

Image preprocessing was conducted using GRETNA toolbox based on Statistical Parametric Mapping (SPM 12; www.fil.ion.ucl.ac.uk/spm/) (Wang et al., 2015). We removed the first ten volumes and performed slice time correction and head motion correction. Functional images were normalized to the EPI template in standard Montreal Neurological Institute (MNI) space provided in SPM12 with an optimum 12-parameter affine transformation and nonlinear deformations, resampled to 3-mm isotropic voxels, and spatially smoothed with a 4-mm full-width at a half-maximum Gaussian kernel. After removing linear trends and temporal band-pass filtering (0.01–0.1 Hz), Friston's twenty-four head motion parameters (including 6 standard head motion parameters, the derivative of the standard motion parameters and the 12 corresponding squared items; see Friston et al., 1996) and three other confounding signals (i.e., white matter, cerebrospinal fluid and global signals) were regressed from the time course of each voxel.

2.5. Graph theory analysis

2.5.1. Network construction and analysis

Ten network nodes were defined based on a recent meta-analysis of language control network during language switching (Luk et al., 2012). We also included the dACC network node in the ROIs given its critical role in models of language control in previous review articles (Calabria et al., 2018; Pliatsikas and Luk, 2016), which included r-fMRI studies. In total, 11 ROI spheres (radius 6 mm) were included in the present study (see Table 2 for the coordinates).

Further, the mean time series for each node were extracted and then correlated with each other to obtain a correlation matrix for each participant. Based on the correlation matrices, we constructed a weighted brain graph by using a set of sparsity thresholds ranging from 0.3 to 0.6 with a step of 0.02 (0.3 ≤ T ≤ 0.6). The sparsity threshold represented the proportion of the present connections to the maximum possible connections within the network. For each participant's brain graph, we calculated both global network properties (i.e., Small-worldness, E_{glob} and E_{loc}) and regional nodal properties (i.e., E_{nodal}, D_{nodal} and B_{nodal}) using the GRETNA toolbox (<https://www.nitrc.org/projects/gretna/>; Wang et al., 2015).

Table 2

Coordinates of eleven regions of interest.

No.	ROI	Abbreviations	MNI Coordinate		
			x	y	z
1	Left middle frontal gyrus (BA46)	L_MFG	-48	19	27
2	Pre-Supplementary Motor Area (BA6)	pre_SMA	2	4	64
3	Left inferior frontal gyrus (BA47)	L_IFG	-33	25	-13
4	Right precentral gyrus (BA6)	R_PrCG	46	-5	-29
5	Right caudate	R_Caudate	17	10	11
6	Left middle temporal gyrus (BA37)	L_MTG	-54	-43	-11
7	Left inferior frontal gyrus (BA44)	L_IFG	-52	21	4
8	Right superior temporal gyrus (BA22)	R_STG	55	-19	-8
9	Left middle frontal gyrus (BA9)	L_MFG	-44	8	31
10	Left caudate	L_Caudate	-11	22	-7
11	Dorsal anterior cingulate cortex	dACC	0	6	44

2.5.2. Statistical analysis

Two-sample t-tests (two-tailed, $p < 0.05$) were performed to detect group differences between Session 1 and Session 2 for both global and regional network properties. As the area under the curve (AUC) could avoid the need for multiple comparisons at individual sparsity points (Fornito et al., 2013), we calculated AUC for each global/regional property. This provides a summary measure that is independent of a single threshold.

Further, partial correlation analyses were conducted to determine the relationships between the network properties, where group differences were detected, and the changes in language switch cost, controlling for L2 AOA and objective language proficiency (i.e., OPT scores).

2.5.3. Validation analysis

To evaluate the reliability of our main analysis on weighted networks, we conducted a validation analysis on binary networks. The AUC, with the same set of sparsity thresholds as in the main analysis, was used in the validation analysis.

2.6. ROI-to-ROI functional connectivity analysis

Following the graph theory analysis, the ROI-to-ROI functional connectivity analyses were performed using CONN toolbox with the same 11 ROIs as used for the graph theory analysis (<https://www.nitrc.org/projects/conn/>; Whitfield-Gabrieli and Nieto-Castanon, 2012). Correlation coefficients were calculated for each participant. Afterwards, the obtained correlation coefficients were Fisher-z transformed. Further, one-sample t-tests were calculated separately for each group to identify significant functional connectivity between the ROIs. Next, paired-sample t-tests were used to examine whether network connectivity changed throughout the one-year L2 courses. Also, partial correlation analyses were conducted to assess the correlation between the brain connectivity, where group differences were detected, and the changes in response times (RT) of switch cost, controlling for L2 AOA and OPT scores. FDR corrections for multiple comparisons were applied at an adjusted significance level of $p < 0.05$.

2.7. Seed-to-voxel functional connectivity analysis

We further conducted seed-to-voxel analyses with the seeds where group differences were detected in graph theory analysis. This allowed us to verify the findings in the ROI-to-ROI functional connectivity

analysis and further explore whether the regions within the language control network were differentially connected to other brain regions outside of the language control network. Temporal correlations were computed between the seed and all other voxels in the brain, resulting in group-level statistics representing Fisher-z transformed correlation coefficient values. Then, paired-samples t-tests as those used in the ROI-to-ROI functional connectivity analysis were applied. In addition, partial correlation analyses were conducted to assess the relationships between the brain connectivity, where group differences were detected, and the changes in response times (RT) of switch cost, controlling for L2 AOA and OPT scores. The results from seed-to-voxel are reported as significant at a voxel-wise threshold of level of $p < 0.001$ (uncorrected) and a cluster-level threshold of $p < 0.05$ (FDR corrected).

3. Results

3.1. Behavioral results

Paired-samples t-tests showed that the participants' self-rated proficiency score in English improved significantly over the course of a one-year L2 courses in the classroom (4.31 vs 4.75, $t(20) = 3.227$, $p < 0.01$). However, Chinese proficiency did not significantly change (6.12 vs 5.96, $t(20) = 0.833$, $p = 0.415$) due to native proficiency for the participants.

For the language switching task, RTs over 2.5 SDs away from the mean for each condition were excluded from the behavioral analysis (cf. Jiao et al., 2020). We only performed statistical analyses on the RTs, as accuracy was generally high for all participants ($>0.95\%$). The switch cost for each language was calculated by subtracting the reaction times in the repeated trials from the switch trials. A repeated-measures 2 (test session: Session 1 vs. Session 2) \times 2 (language: L1 vs. L2) ANOVA was performed with switch cost as the dependent variable. There was a significant effect of test session, $F(1, 19) = 4.634$, $p = 0.044$, $\eta^2 = 0.196$, indicating that the switch cost at Session 2 is significantly smaller than those at Session 1. There was also a significant main effect of language, $F(1, 19) = 14.203$, $p = 0.001$, $\eta^2 = 0.428$, indicating significantly larger switch cost in L2 than in L1. However, there was no significant interaction between test session and language, $F(1, 19) = 1.590$, $p = 0.223$, $\eta^2 = 0.077$, indicating both L2-L1 switch cost and L1-L2 switch cost numerically decreased at Session 2 than Session 1 (see Fig. 2).

3.2. Graph theory results

3.2.1. Global network properties

For the global network properties, paired-samples t-tests indicated no significant alterations between Session 1 and Session 2 in Small-worldness ($t = 1.971$, $p = 0.063$), global efficiency

($t = -1.686$, $p = 0.108$), and local efficiency ($t = -1.42$, $p = 0.172$) (see Table 3).

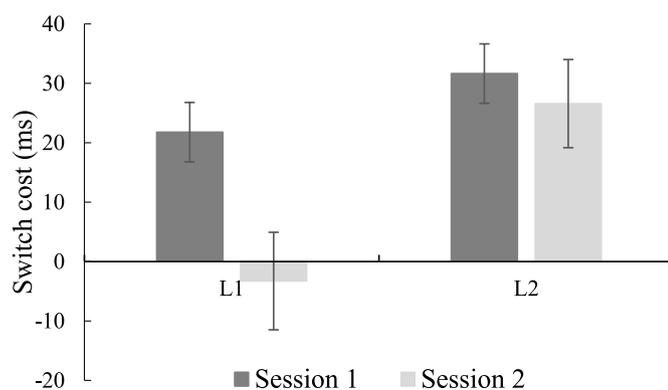


Fig. 2. Language switch cost for both languages at Session 1 and Session 2.

Table 3

Group comparisons of AUC values (mean \pm SD) for global network properties.

	σ	E_{glob}	E_{loc}
Session 1	1.333 \pm 0.243	0.053 \pm 0.006	0.060 \pm 0.012
Session 2	1.223 \pm 0.161	0.058 \pm 0.014	0.066 \pm 0.021
p	0.063	0.108	0.172

3.2.2. Regional nodal properties

For the regional nodal properties, we only found a decreased nodal betweenness in dACC ($t = 2.458$, $p = 0.024$) at Session 2 as compared to Session 1. There were no differences for the other nodes in any regional nodal properties ($ps > 0.05$) (see Fig. 3).

More importantly, we found that the decrease in nodal betweenness of dACC was significantly correlated with the decrease in the language switch cost ($r = 0.545$, $p = 0.019$). Specifically, the smaller the nodal betweenness of dACC, the greater the switching cost decrease from Session 1 to Session 2. Further analyses indicated that the decrease in nodal betweenness of dACC was significantly correlated with the decrease in the L2-L1 language switch cost ($r = 0.573$, $p = 0.013$), but not in the L1-L2 language switch cost ($r = 0.093$, $p = 0.714$) (see Fig. 4).

3.2.3. Results of validation analysis

The validation analysis on binary network did not reveal significant group differences in the global network properties ($ps > 0.05$). For the regional nodal properties, there was a smaller nodal betweenness in dACC at Session 2 than Session 1 ($t = 2.215$, $p = 0.039$). Further, the partial correlation analysis also showed that the decrease in nodal betweenness of dACC was significantly correlated with the decrease in the language switch cost ($r = 0.617$, $p = 0.006$). More specifically, we found the decrease in nodal betweenness of dACC was significantly correlated with the decrease in the language switch cost in L1 ($r = 0.587$, $p = 0.011$), but not in L2 ($r = 0.188$, $p = 0.455$), which were in line with the results of the weighted networks.

3.3. ROI-to-ROI functional connectivity results

In the ROI-to-ROI connectivity analysis within the language control network with 11 ROIs, we only found increased connectivity between dACC and pre_SMA, reflected by the Fisher's z-values, at Session 2 as compared to Session 1 ($t = 16.44$, $p < 0.001$; see Fig. 5, left panel). Further correlation analyses indicated no significant correlation between the increase in brain connectivity and the decrease in behavioral language switch cost ($r = -0.355$, $p = 0.149$). However, we found the increase in brain connectivity between dACC and pre_SMA correlated negatively with the decrease in the L1-L2 language switch cost ($r = -0.541$, $p = 0.020$), but not in the L2-L1 language switch cost ($r = 0.016$, $p = 0.951$) (see Fig. 5, right panel).

3.4. Seed-to-voxel functional connectivity results

In the seed-to-voxel connectivity analysis, we only found increased functional connectivity between the dACC seed and a cluster in the pre_SMA ($t = 21.05$, $p < 0.001$), and this increased connectivity correlated significantly with the decrease in behavioral L1-L2 language switch cost ($r = -0.535$, $p = 0.022$), but not in the L2-L1 language switch cost ($r = 0.001$, $p = 0.996$) (Session 2 – Session 1; see Fig. 6).

4. Discussion

In the present study, we investigated how long-term classroom L2 learning shapes the bilingual language control network in the resting brain. Chinese college freshmen majoring in English underwent resting-state scanning before and after one year of L2 learning in the classroom. Graph theory analysis showed a decreased nodal betweenness in the dACC from Session 1 to Session 2. This decrease in dACC positively

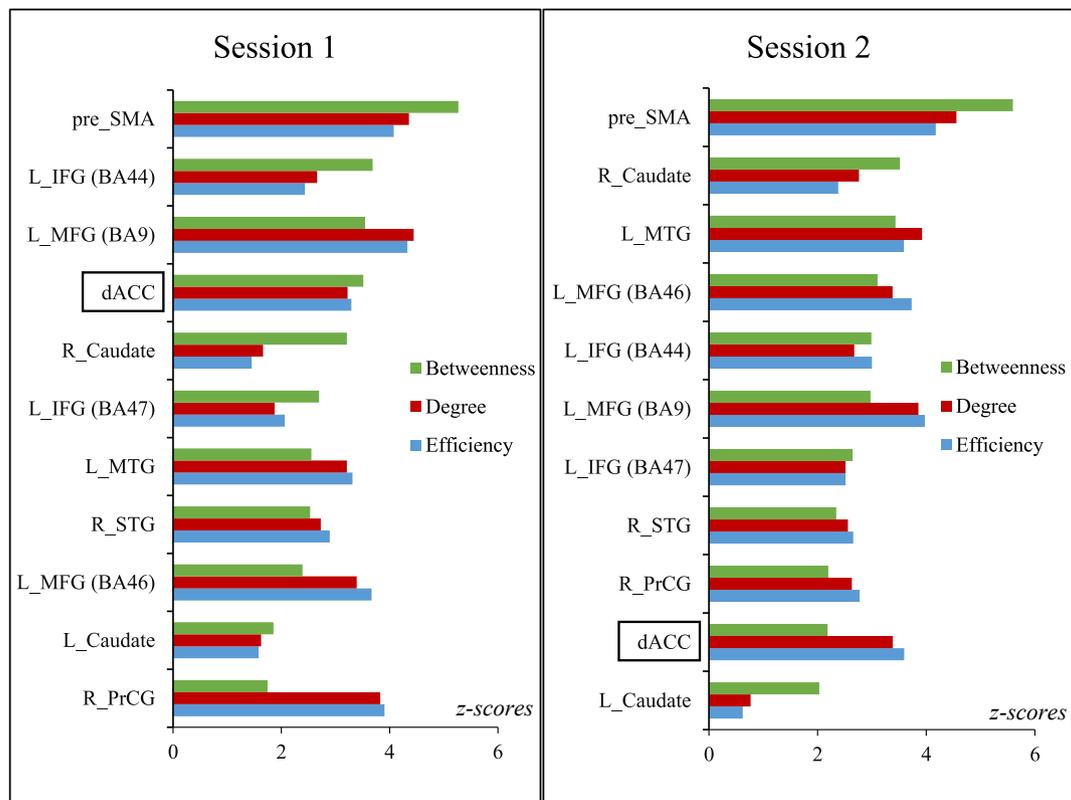


Fig. 3. Node-specific values in efficiency, degree and betweenness. The nodes were sorted by betweenness in descending order for both Session 1 and Session 2. For the convenience of visualization, the raw values for each nodal property were transformed into z-scores.

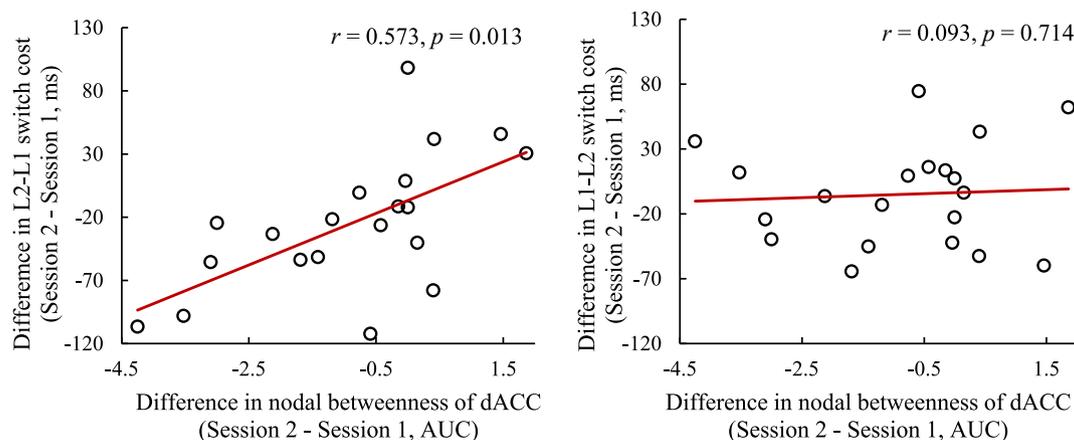


Fig. 4. Association between nodal betweenness of dACC and behavioral performance on the language switching task.

correlated with the decrease in the L2-L1 language switch cost. Furthermore, both the ROI-to-ROI connectivity analysis and the seed-to-voxel connectivity analysis revealed that the connectivity between dACC and pre-SMA significantly increased with classroom L2 learning. This increase was correlated with the decrease in behavioral L1-L2 language switch cost. These results suggest that classroom L2 learning induces adaptive changes in brain networks involved in bilingual language control.

4.1. Neuroplasticity in topologies of the language control network induced by L2 learning

Graph theory is the most common tool used to investigate the topological properties of brain networks in people with diseases (Weizman

et al., 2018; Zhang et al., 2019), but it is not as widely used in bilingualism and L2 learning research. The current study is one of the first to employ this method in relation to the L2 learning. It revealed that long-term classroom L2 learning modulated the regional, but not the global, topologies of the language control network.

For the regional topological properties, participants showed a decreased nodal betweenness in dACC from Session 1 to Session 2. The decreased nodal betweenness indicates fewer shortest paths between the nodes within the brain network that pass through one node. A node with lower betweenness has less control over the network because less information will pass through that node. Moreover, to our knowledge, the dACC plays an important role in conflict monitoring during language control (Abutalebi et al., 2013). Hence, we speculated that our finding of decreased nodal betweenness in the dACC might more efficiently use of

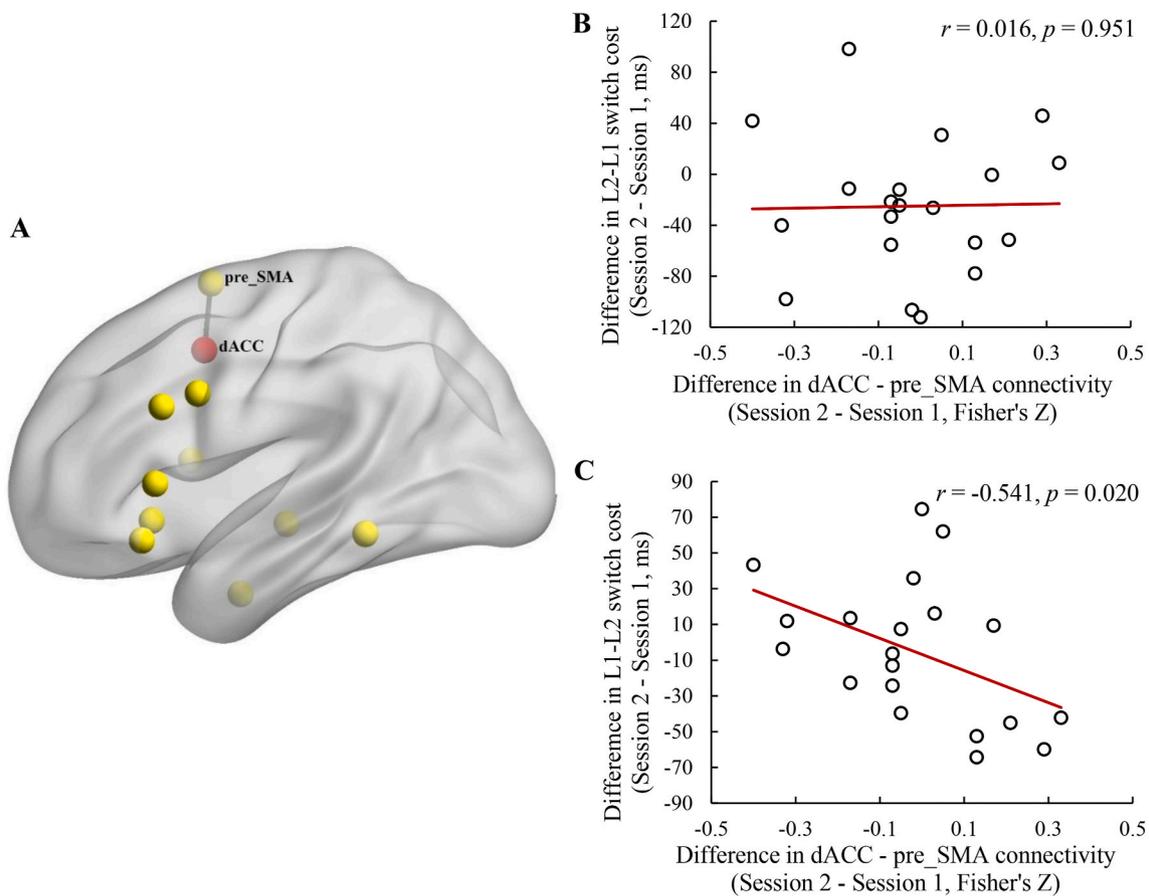


Fig. 5. Association between ROI-to-ROI connectivity (Fisher's z) and behavioral performance on the language switching task. **A**, Stronger dACC – pre_SMA connectivity at Session 2 than Session 1. **B**, Low correlation between increased dACC – pre_SMA functional connectivity (Fisher's z) and reduction in the L2-L1 language switch cost during language switching. **C**, Correlation between increased dACC – pre_SMA functional connectivity (Fisher's z) and reduction in the L1-L2 language switch cost during language switching.

the area. This interpretation comes from the idea that when there is no need any more for collaboration with other brain areas, decreases in the betweenness are found. Next to increased efficiency, the dACC might also become more specialized in conflict monitoring during language control. The present results are in line with one previous study that also found reduced activation of the dACC, meaning that bilinguals could more efficiently monitor conflict after short language-switching training (Kang et al., 2017). Critically, these findings support some of the predictions from the DRM and also the Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) framework (Grundy et al., 2017). Specifically, it supports the idea that language control (i.e., dACC) demands decrease on frontal monitoring structures with prolonged L2 learning. Further, this decreased nodal betweenness in dACC only correlated with the decrease in the L2-L1 language switch cost and not the L1-L2 language switch cost. Previous research also revealed that this area was always activated during switching from L1 to L2, but not during switching from L2 to L1 for non-proficient bilinguals (Wang et al., 2007). This might indicate that within the language control network the dACC became less important during L2-L1 language switching with increased L2 learning.

For the global network properties, no significant alterations were observed between Session 1 and Session 2 in small-worldness, global efficiency, and local efficiency. This is inconsistent with previous studies which showed that learning a sign language could induce some changes in global network properties (Liu et al., 2017). We speculated that two potential factors might lead to the non-significant results: the sample size and the L2 learning time in the current study. Specifically, there were only 20 participants in our experiment, which might have been too low a number to detect potentially smaller effects. On the other hand,

the one-year L2 learning period was not too short to induce neuroplasticity in global network properties. Future studies should track more participants over two or more years, to further investigate how longitudinal L2 learning experience shapes the topological properties of brain networks.

Note that due to increased expression of concerns regarding the reproducibility of psychological and MRI findings (Collaboration, 2015; Poldrack et al., 2017), a validation analysis was conducted here. This analysis further confirmed the reliability of our findings for both the regional and global network properties.

4.2. Neuroplasticity in functional connectivity of the language control network induced by L2 learning

In the ROI-to-ROI connectivity analysis, we found that the connectivity between dACC and pre-SMA significantly increased with classroom L2 learning. It has been reported that both the dACC and the pre-SMA were associated with monitoring language conflict (Abutalebi and Green, 2007; Abutalebi et al., 2011; Luk et al., 2012). The activation of both these regions has consistently been reported during language switching in bilinguals (Abutalebi and Green, 2007; Branzi et al., 2015; Calabria et al., 2018; Green and Abutalebi, 2016). The links between these two regions may reflect their cooperative function during monitoring one's bilingual language environment and resolve competition between the languages. Thus, in the present study, the increased connectivity strength between dACC and pre-SMA might suggest that participants' ability to monitor conflict (i.e., language control abilities) improved after long-term L2 learning in a classroom setting. It should be

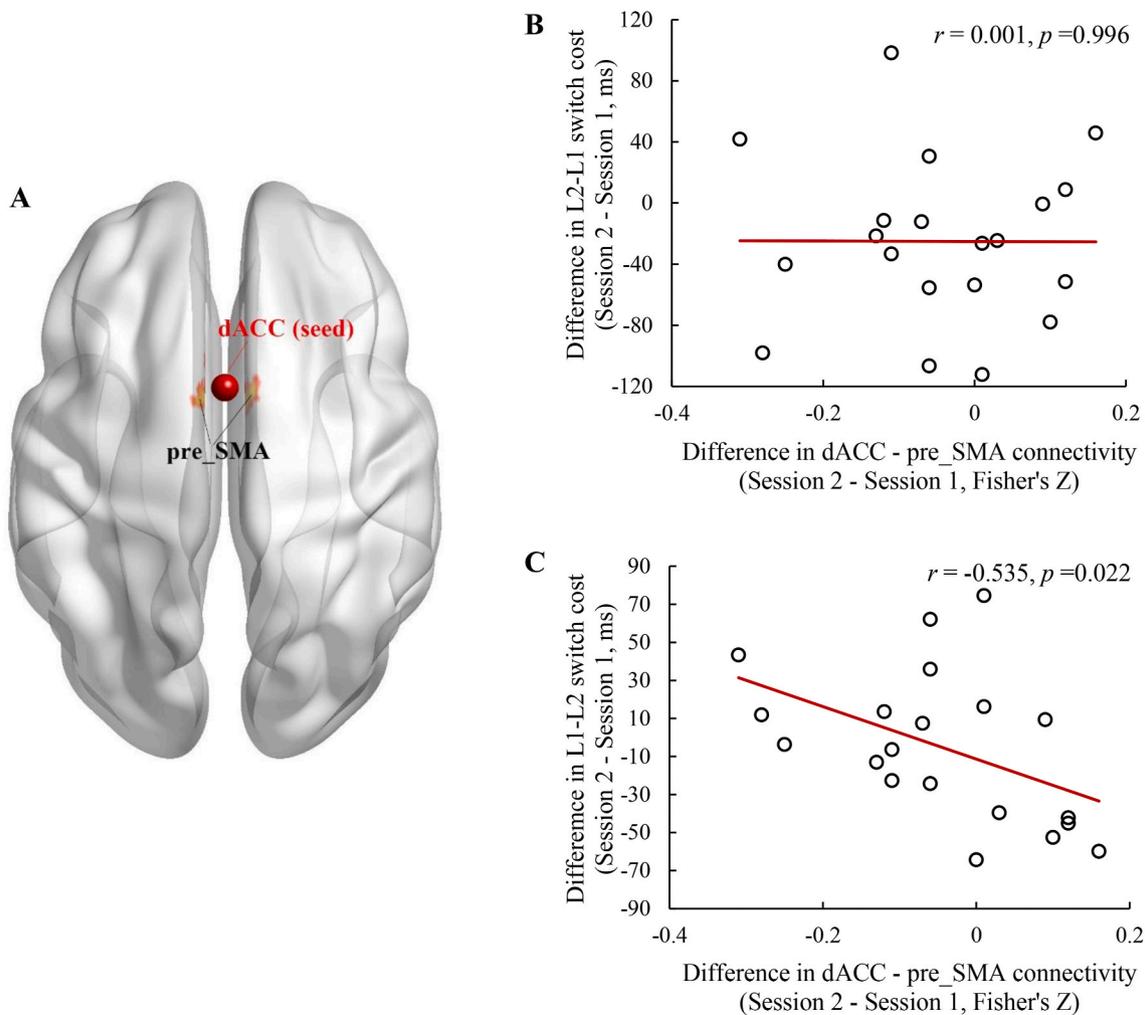


Fig. 6. Association between seed-to-voxel connectivity (Fisher's z) and behavioral performance on the language switching task. **A**, Stronger dACC – pre_SMA connectivity at Session 2 than Session 1. **B**, Low correlation between increased dACC – pre_SMA functional connectivity (Fisher's Z) and reduction in the L2-L1 language switch cost during language switching. **C**, Correlation between increased dACC – pre_SMA functional connectivity (Fisher's Z) and reduction in the L1-L2 language switch cost during language switching.

emphasized that this concerns an increase in resting-state *functional* connectivity, which was consistent with previous studies focusing on *structural* connectivity. Those studies observed that language learning decreased isotropic diffusivity in white matter, signifying more efficient communication between frontal, parietal, and subcortical language-related regions (Pliatsikas, 2019). In all, these findings indicate that L2 learning optimizes the way the brain functions.

Furthermore, the negative correlation between the neural changes in the functional connectivity and the decrease in behavioral L1-L2 language switch cost indicated a lesser need for control during language switching from L1 to L2. This finding is consistent with previous work indicating that dACC/pre-SMA appeared to be activated exclusively during L2 naming (after naming in L1) (Branzi et al., 2015; Wang et al., 2007). Given that the bilinguals in the current study were not proficient in their L2, they may need to rely more on monitoring processes during L2 naming (Branzi et al., 2015). In contrast, they may not require monitoring processes to the same extent during their proficient L1 naming.

The findings in seed-to-voxel connectivity analysis was consistent with those in the ROI-to-ROI connectivity analysis. This confirmed the reliability of our findings. Taken together, both functional connectivity analyses suggested that long-term classroom L2 learning could induce neuroplasticity of the resting-state network during language control.

4.3. Limitations

It is noted that, our study lacked a control group and someone may argue that the decrease in switch cost was related to task-related training. To address this limitation, we added a behavioral control group. Specifically, 25 Chinese college freshmen (22 females, mean age: 19.32 years, SD: 0.75; range: 18–20) who were not majoring in foreign languages (i.e., self-rated proficiency in Chinese = 5.94, self-rated proficiency in English = 4.09, $t = 9.323$, $p < 0.001$) were recruited to behaviorally complete the language switching task twice about one month apart. The results showed that the language switch cost towards both L1 (10 ms vs. 7 ms, $t = 0.202$, $p > 0.05$) and L2 (14 ms vs. 11 ms, $t = 0.473$, $p > 0.05$) remained the same between Session 1 and Session 2. This is in contrast to the decreased switch cost for our experimental group, suggesting the observed behavioral effect on switch cost in our experimental group was specifically related to L2 learning rather than a general learning experience at university.

5. Conclusion

Overall, the current study examined neural changes in resting-state networks related to language control over one year of classroom L2 learning. We found that the brain mechanisms change with long-term L2 learning. These changes were specific to brain regions of importance to

language control for bilinguals. These findings are generally consistent with the central tenets of the ACH (Green and Abutalebi, 2013) and DRM (Pliatsikas, 2020), two theories on the adaptive features of bilingual language control mechanisms. Compared to the studies thus far reported in the literature (DeLuca et al., 2018; Li et al., 2014; Zou et al., 2012), which mainly focused on structural neural adaptations, our study revealed functional adaptations. Therefore, our contribution here was demonstrating the neuroplasticity of language control network during resting-state as induced by L2 learning in a naturalistic classroom.

More specifically, our findings suggest that classroom L2 learning may lead to decreases in nodal betweenness of dACC and increases in connectivity strength between dACC and pre-SMA. These are two key brain regions that have been implicated in bilingual language control in previous literature (Abutalebi and Green, 2016; Branzi et al., 2015). Critically, the observed neural changes were correlated with participants' behavioral performance (i.e., the reduction in switch cost from L2 to L1). Taken together, these findings provide considerable support for the idea that long periods of L2 classroom learning may induce significant neuroplastic changes in the language control network during the resting brain.

Credit author statement

Cong Liu: Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Lu Jiao:** Conceptualization, Investigation, Writing - review & editing. **Zilong Li:** Formal analysis, Software, Writing - review & editing. **Kalinka Timmer:** Writing - review & editing. **Ruiming Wang:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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