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Original Research

Altered Cerebro-Cerebellar Functional Connectivity Associated With Working Memory Decline After Sleep Deprivation

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Abstract

Background: It has been demonstrated that the cerebellum plays a critical role not only in motor function but also in cognitive function. Numerous studies have revealed that acute sleep deprivation (SD) alters the functional connectivity (FC) in the cerebral cortex associated with declining working memory (WM). However, the relationship between the altered cerebro-cerebellar FC and white matter damage following acute sleep deprivation remains elusive. **Methods**: In this study, 26 healthy participants with regular sleep conducted an n-back task and had resting-state functional magnetic resonance imaging (fMRI) scans before and after 24 h of SD. The FC between the cerebrum and cerebellum and its relationship with WM function were analyzed in recruited participants. **Results**: Our results showed a significantly longer RT for the 1-back and 2-back tasks and lower accuracy of the 2-back task after SD. We found a marked reduction in FC between ten pairs of regions in the cerebellum and cerebrum after SD. Furthermore, a decline in WM performance was positively correlated with the changed FC between the left precentral gyrus and the right lobule X of the cerebellum. **Conclusion**: Our findings indicate that the impaired FC between the cerebellum and cortical areas may contribute to the decline in WM after acute SD. **Clinical Trial Registration**: No: ChiCTR2000039858. Registered 12 November, 2020, https://www.chictr.org.cn/showproj.html?proj=63916.

Keywords: sleep deprivation; the cerebrum; the cerebellum; functional connectivity; working memory

1. Introduction

Sleep deprivation (SD) is very common in modern society, with a sleep duration of less than four hours on a typical 24-hour day, leading to abnormal changes in body and mood [1]. Due to unhealthy lifestyle habits and sleep disorders, SD causes a series of negative effects, especially on cognitive function, including memory impairment, lack of attention, mood changes, and slow thinking [2–4]. Working memory (WM) is a crucial component of cognitive performance that involves numerous brain regions, including the parietal lobe and the cingulate cortex [5]. Acute SD markedly diminishes the accuracy and omission rate of WM [6,7]. The mechanism that underlies the decline in WM performance after acute SD has been investigated using functional magnetic resonance imaging (fMRI) [8,9]. A previous neuroimaging study has suggested that WM function is linked to the volume of gray matter in the supplementary motor cortex after acute SD [10] .

Resting-state functional connectivity (FC) can reflect the effects of neural networks under some condition [11]. Multiple studies had demonstrated the altered FCs among the default model network, salience network, dorsal attention network and frontoparietal network after SD [9,12,13]. Our previous study also revealed disrupted FCs within WM network, which were associated with WM decline after SD [14]. These connections are almost cortico-cortical, whereas the cerebellum is seldom mentioned [11]. Growing evidence has indicated that the cerebellum is essential for cognitive function and motor ability [15]. Different regions of the cerebellum take part in different subsystems of the model of WM [16]. Higher volumes of cerebellar subregions were associated with better performance of WM, such as Crus I and VIIIa [17]. Furthermore, sleep can also help process and consolidate procedural memory which is depended on cerebellum [18,19]. Previous studies have illustrated an abnormal cerebellum and poor memory in some sleep disorders [18,20]. Importantly, numerous studies have suggested that SD decreases gray matter volume in the right cerebellum anterior and posterior lobes [21–23]. Furthermore, numerous investigations have indicated alterations in the cerebro-cerebellar FC in WM [24–26]. The relationship between the altered cerebro-cerebellar FC and WM impairments after acute SD remains unclear.

To fill this gap, we hypothesized that altered cerebro-cerebellar FC contributes to reduced WM function after acute SD. We recruited healthy individuals with regular sleep and collected resting-state fMRI scans before and after 24 h of SD to verify our hypothesis. Additionally, we

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administered the n-back task to assess WM performance in the enrolled participants. Subsequently, we investigated the correlation between the altered cerebro-cerebellar FC and WM performance in individuals with acute SD.

2. Materials and Methods

2.1 Participants

The sample size for our study was calculated using G*Power, which had a standard effect size of 0.5 and a power of 0.8, with an error probability of 0.05 [27]. The participants who were recruited from November 2020 to May 2021 included a total of 26 healthy college students, 13 of whom were females, ranging in age from 20 to 30 years (25.03 $\pm$ 1.72 years), and having an education duration of 17.92 $\pm$ 1.38 years. The participants who were enrolled in the study were required to meet the following criteria: (1) Pittsburgh Sleep Quality Index (PSQI) score less than 5; (2) regular sleep patterns without predominant morning or evening tendencies; (3) right-handedness; (4) absence of neurological or psychiatric disorders; (5) no exposure to stressful stimuli; (6) no pattern of dependence on caffeine, smoking, alcohol or drug addictions; (7) no magnetic resonance imaging (MRI) contraindications. The Ethics Committee of Beijing Anding Hospital, affiliated with Capital Medical University, approved the study protocol (Approved No: 202065FS-2, number of clinical registrations: ChiCTR2000039858). This study was conducted in accordance with the Declaration of Helsinki, and informed consent was obtained from each enrolled patient prior to the study.

2.2 Study Procedure

Consistent with our prior research [14], each participant went to the laboratory twice. While they were being provided with a comprehensive summary of the investigation, they were required to sign a form indicating their informed consent at the first visit. During the second visit, they had to be awake by 7:00 am and return to the laboratory by 8:00 am for 24-hour SD. All enrolled participants were required to stay awake and refrain from drinking tea, alcohol, or coffee throughout the trial, and the researchers kept track of their turns to ensure that they were alert. Each participant had two MRI scans before and after 24 hour SD, respectively. We performed the 250 s T1 and 490 s resting-state scans during the first MRI scan, and the 490-s resting-state scan during the second MRI scan approximately 7:00 am the following day. All subjects were instructed to remain awake during the scanning, and no participants who fell asleep during the fMRI scan were removed.

2.3 Cognitive Assessment

For the purpose of assessing WM performance both before and after 24 hours of sleep deprivation, the n-back task was utilized in this study. Throughout the assignments of 0-back, 1-back, and 2-back, a series of letters was shown in the middle of the screen of the computer (Fig. 1) [8]. After a blank screen that lasted for two thousand milliseconds, the letter was displayed for five hundred milliseconds. It was the participants' responsibility to respond to each trial when they were at the 0-back level. This served as a control condition that allowed the task to be adjusted. During the 1-back task, participants were required to click the mouse button on either the left or right side of the screen whenever the letters of the two consecutive trials were the same. In the 2-back task, participants indicated whether the letter appeared two trials prior. The exercise comprised nine blocks with 270 trials, conducted over 11 minutes using E-prime 2.0 (Psychology Software Tools, Inc, Pittsburgh, PA, USA). An experienced neuropsychologist followed a set of predetermined criteria in order to evaluate the subjects' response times (RT) and accuracy while participating in this task.

2.4 MRI Acquisition

MRI was performed at Beijing Anding Hospital in Beijing, China, using a Siemens 3.0 Tesla Prisma (Siemens, Erlangen, Germany) in order to examine these participants.

During the MRI scan, the participants were required to remain still, keep their eyes closed, and avoid falling asleep. In order to avoid falling asleep during the MRI scan, the participants were instructed to maintain a standstill, keep their eyes closed, and refrain from moving about. Additionally, participants were told to completely immobilize their foam head support in order to prevent any movement of their heads. For the purpose of acquiring resting-state fMRI data, a single-shot, gradient-recalled echo-planar imaging sequence was utilized. Using a single-shot, gradient-recalled echo-planar imaging method, the resting-state fMRI data was obtained. The following information is included [28]: 180 volumes, 32 interleaved axial slices, 90° flip angle, 64 $\times$ 64 matrix, 1 mm gap, 225 mm $\times$ 225 mm field of view, and 3.5 mm slice thickness, echotime = 30 ms, and repetition time = 2000 ms. A rapid gradient-echo sequence with T1-weighted multiecho magnetization preparation was applied to acquire high-resolution structural images.

2.5 Data Processing

DPABISurf (http://rfmri.org/DPABISurf), which was created by Yan *et al.* [29], was utilized in order to carry out image processing [30]. In accordance with the information presented before, a surface-based image preparation pipeline was utilized [29]. Firstly, the T1 images were transformed into the brain imaging data structure (BIDS) dataset. Subsequently, the data underwent correction for intensity non-uniformity using N4BiasFieldCorrection, as supplied by ANTs version 2.3.3 (https://github.com/ANTsX/ANTs) [31]. The remaining brain tissues were divided into cerebrospinal fluid, white matter, and gray matter using the BET (FSL5.0.9, http://neuro.debian.net/pkgs/fsl-5.0-core.html) after the resulting images were skull-stripped

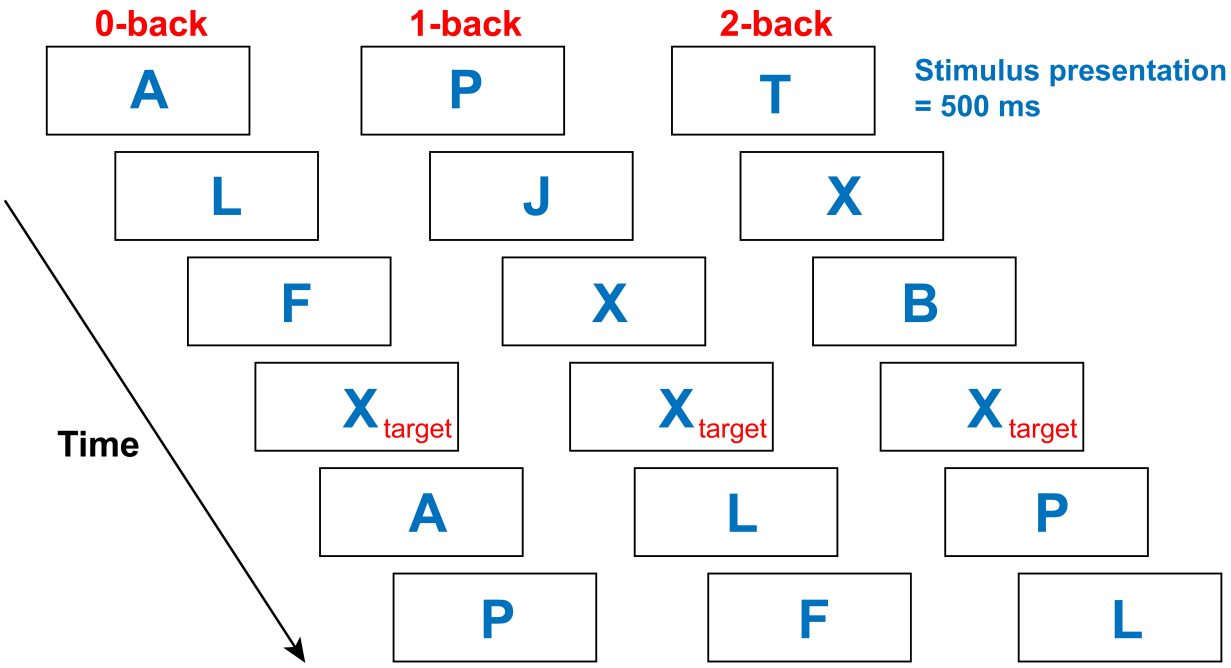

Fig. 1. A visual depiction of the verbal N-back paradigm. The intertrial period was 2000 ms, and stimuli were presented on the screen for 500 ms.

using OASIS30ANTs as the target template. A standard approach was utilized, which included the incorporation of segmentations of the cortical grey matter from Mindboggle (https://github.com/nipy/mindboggle) that were created using artificial neural networks (ANTs). This was done in order to improve the previously calculated brain mask [32]. Using brain-extracted versions of both the T1 reference and the T1 template, volume-based spatial normalization to the MNI152NLin2009cAsym standard space was carried out via nonlinear registration using antsRegistration (ANTs 2.3.3). Simultaneously, the ICBM 152 Nonlinear Asymmetrical template version 2009c (Montreal Neurological Institute, Montreal, QU, Canada) was selected for spatial normalization.

For resting-state fMRI data, a modified approach of fMRIPrep was applied to construct the reference volume and its skull-stripped version [33]. Susceptibility distortion correction (SDC) was eliminated. Bbregister (FreeSurfer, https://freesurfer.net/), leveraging boundary-based registration, was exployed for co-registering the fMRI reference and T1 reference. Furthermore, slice timing was modified using 3dTshift from analysis of functional neuroimages (AFNI) (https://afni.nimh.nih.gov/afni), and spatiotemporal filtering was executed with mcflirt (FSL, https://fsl.fmrib.ox.ac.uk/fsl/fslwiki). The blood-oxygen-level-dependent (BOLD) time-series were resampled into standard space, yielding a preprocessed BOLD run in MNI 152 NLin2009c Asym space. Concurrently, framewise displacement (FD), detrended variability of available repeats statistics (DVARS), and three region-specific global signals were calculated from the preprocessed BOLD data. Additionally, a compilation of physiological regressors was assembled to enhance component-based noise reduction. Frames that exceeded a threshold of 0.5 mm FD or 1.5 standardized DVARS were classified as motion outliers, and the BOLD was devoid of the aforementioned components. ANTs Apply Transforms were employed to accomplish gridded (volumetric) resampling, which reduced the smoothing effects of the additional kernels by utilizing Lanczos interpolation.

The automated anatomical atlas 3 (AAL3) was applied to extract BOLD signals for 166 regions of interests (ROIs), which included the 26 sub-regions (95–120 labels) of the cerebellum and 140 sub-regions of the cerebrum (1–94 and 121–166 labels) [34]. Pearson's correlation coefficient of the BOLD data was employed to evaluate the FC between any two ROI. The FC values were subsequently transformed using Fisher's z-score.

2.6 Statistical Analysis

An analysis of variance (ANOVA) with repeated measurements was carried out in order to investigate the performance of WM under the circumstances of restful wakefulness (RW) and SD conditions. Moreover, we conducted Pearson's correlations between the alterations in RT and accuracy of one-back and two-back tasks and the changed cerebro-cerebellar FC in the RW and SD states. Taking into consideration the multiple comparisons, the false discovery rate (FDR) was utilized (with the significance level adjusted to $p < 0.05$).

Table 1. Results of N-back tasks (RW state vs. SD state).

	One-back task			Two-back task		
	RW	SD	*p* value	RW	SD	*p* value
RT (ms)	526.36 ± 19.31	552.49 ± 15.46	0.014	708.56 ± 35.88	719.01 ± 31.32	0.690
ACC	0.90 (0.86–0.97)	0.92 (0.88–0.97)	0.889	0.87 (0.83–0.93)	0.81 ± 0.03	0.070

ACC, accuracy; RT, reaction time; RW, rested wakefulness; SD, sleep deprivation.

Table 2. Altered FC between the cerebellum and cerebrum after SD.

	T value	*p* value
The right lobule X of cerebellum and left precentral gyrus	–3.778	0.0007
The right lobule X of cerebellum and left amygdala	–3.753	0.0008
The right lobule X of cerebellum and left ventral anterior of thalamus	–3.848	0.0006
The right lobule III of cerebellum and left ventral anterior of thalamus	–5.429	<0.0001
The right lobule III of cerebellum and left lateral posterior of thalamus	–5.031	<0.0001
The right lobule III of cerebellum and right lateral posterior of thalamus	–4.016	0.0004
The right lobule III of cerebellum and left intralaminar of thalamus	–4.093	0.0003
The right lobule III of cerebellum and left reuniens of thalamus	–3.754	0.0008
The left lobule III cerebellum and left ventral anterior of thalamus	–4.164	0.0003
The left lobule III cerebellum and left lateral posterior of thalamus	–4.396	0.0001

FC, functional connectivity.

3. Results

3.1 WM Performance

A paired-sample *t*-test was carried out in order to compare the RT and accuracy of the one-back and two-back tasks between the RW and SD states (Table 1). The results showed that the SD state had a significantly longer RT for the one-back task compared to the RW state ($p = 0.014$), but there was no significant difference observed for the two-back task ($p = 0.690$). When compared to the RW state, the SD state had a decrease in task accuracy, while the one-back task ($p = 0.889$) and the two-back ($p = 0.070$) tasks did not show any significant differences.

3.2 Altered FC Between the Cerebellum and Cerebrum After SD

In comparison to the RW condition, we observed a marked reduction in FC between ten pairs of areas in the cerebellum and cerebrum after SD, containing the right lobule X of the cerebellum and left precentral gyrus, right lobule X of the cerebellum and left amygdala, right lobule X of the cerebellum and left ventral anterior thalamus, right lobule III of the cerebellum and left ventral anterior thalamus, right lobule III of the cerebellum and left lateral posterior thalamus, right lobule III of the cerebellum and right lateral posterior thalamus, right lobule III of the cerebellum and right lateral posterior thalamus, right lobule III of the cerebellum and left intralaminar thalamus, right lobule III of the cerebellum and left reuniens of the thalamus, left lobule III cerebellum, and left ventral posterior thalamus. No significantly enhanced FC were detected. The data is depicted in Table 2 and Fig. 2.

3.3 Correlation Analysis

We conducted a correlation analysis examining the relationship between variations in the RT of one-back and two-back tasks and altered FC between the cerebellum and cerebrum. Our findings indicated a positive correlation between the change in RT for the two-back task and the altered FC between the right lobule X of the cerebellum and the left precentral gyrus ($r = 0.445$, $p = 0.023$, Fig. 3). Additionally, we investigated the correlation between changes in accuracy and altered FC between the cerebellum and cerebrum, but found no significant association.

4. Discussion

In this study, we purposed to analyze the changed FC between the cerebellum and cerebrum to predict WM impairment after acute SD. The 10 pairs of regions between the cerebellum and cerebrum showed a significantly decreased FC after SD. Furthermore, the alteration in FC between the right lobule X of the cerebellum and left precentral gyrus exhibited a positive correlation with a decrease in WM performance. These results suggest that modified FC between the right lobule X of the cerebellum and left precentral gyrus might predict WM impairment after acute SD.

Altered FC in the cerebrum regions is mainly involved in the thalamus, amygdala, and precentral gyrus after acute SD. A recent study revealed an increased amplitude of low-frequency fluctuation (ALFF) in the thalamus after 24 h SD [35]. Another study confirmed that increased FC between the thalamus and the default mode network is associated with worse WM performance [36]. Consistent with our results, these findings indicate that alterations in tha-

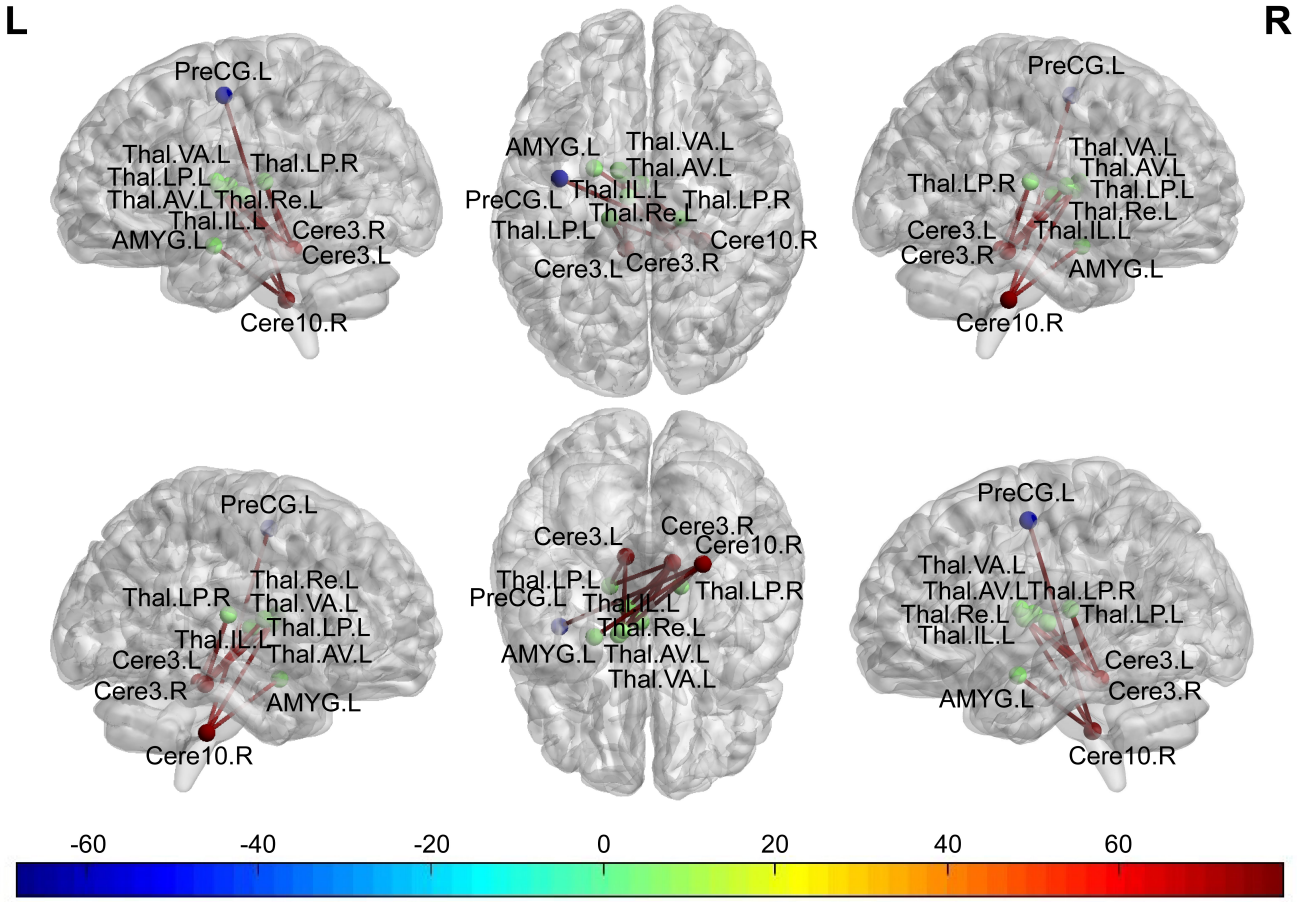

Fig. 2. The functional connection between the cerebrum and cerebellum has been substantially altered as a result of SD, as illustrated in the schematic diagram. The mean strength of functional connectivity between brain regions is denoted by the colors as indicated in the color bar.

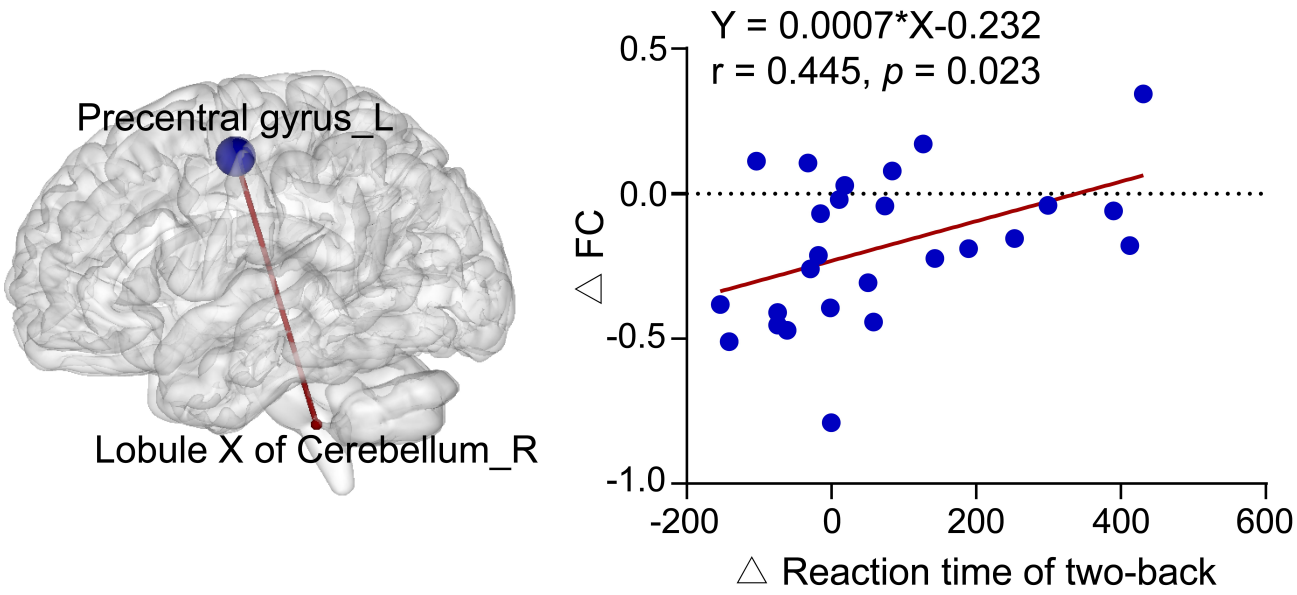

Fig. 3. The association between the reaction time of two-back and the altered FC between the right lobule X of the cerebellum and the left precentral gyrus.

lamic activity are associated with WM performance after SD. The amygdala has a critical function in emotional processing and contributes to fear memory storage after SD [37]. Importantly, increased connection strength between the amygdala and cerebellum has been confirmed to be associated with emotional enhancement of episodic memory [38]. The precentral gyrus is involved in motor functions and cognitive processing [39]. Previous findings demonstrated that the FC between the putamen and bilateral precentral gyrus was significantly reduced after 36 h of SD, which may be associated with impaired motor perception [40]. Another study demonstrated decreased FC between the left hippocampal and bilateral precentral gyri during the n-back task after acute SD, which implied a role for the precentral gyrus during the WM task [41]. Taken together, these findings provide evidence for the role of these cerebral regions in cognitive and emotional processing after SD.

Our findings also showed altered FC in the cerebellar regions largely implicated in lobules III and X after acute SD. Lobule III is located in the cerebellum anterior lobe, builds functional circuits with sensory areas, including the thalamus, and is responsible for motor execution [42]. It had been demonstrated that the Motor preparation and execution were impaired after acute SD [43]. Considering the altered activity of the thalamus after SD, we proposed that the decreased FC between lobule III and the subregions of the thalamus might be the neuronal mechanism responsible for SD-induced impaired motor execution. Lobule X comprise a segment of the cerebellar posterior lobe, which is integral to cognitive functions, including WM, language, and motor planning [42]. Several studies have confirmed that lobules VI/Crus I and VII and the right VIIIA are activated during WM tasks [44,45]. These regions are also located in the posterior lobe of the cerebellum. Notably, the precentral gyrus and cerebellar regions were activated in healthy subjects during the Sternberg WM task [46]. Our results also revealed that the change in FC between right lobule X of the cerebellum and left precentral gyrus was positively correlated with a decline in WM performance, which suggested the disparity between the FC-RT and FC-SD relationships. RT is often associated with the efficiency of neural processing and the speed of information transfer between brain regions. We speculated that it might be due to the learning effect of N-back or large individual differences responding to SD [47,48]. Hence, the reduced FC between the right lobule X of the cerebellum and the left precentral gyrus might represent the neuronal mechanism underlying WM impairment after acute SD. Overall, this finding is consistent with our hypothesis and provides new insights into the role of cerebro-cerebellar FC in predicting WM decline following acute SD.

However, this study had several limitations. First, only participants aged 20–30 years were recruited. Our results cannot be expanded to other age groups. Future research should recruit healthy participants from a wider age spectrum. Second, the learning effect in the n-back task should be noted, which may explain the lack of significant differences in the accuracy (ACC) between the SD and RW states. Further studies with separate resting control groups are required. Thirdly, this study did not include a control group, in which healthy participants complete the same tasks after normal sleep. Further studies are required to include the control group to accurately distinguish between the effects of SD and task repetition. Fourthly, we did not collect the average sleep time of each participant, which might limit the comprehensiveness of the analysis of the effects of acute SD on WM and cerebro-cerebellar FC. Future researches are required to record average sleep times to mitigate the effects of SD on cognitive function. Finally, acute SD and chronic SD differ significantly in the duration, impact on the cognitive function by disrupting brain activity. Future researches are needed to further distinguish the neural mechanisms of acute and chronic SD on working memory.

5. Conclusion

In conclusion, our findings revealed an association between WM performance and altered cerebro-cerebellar FC in acute SD. The altered FC between the right lobule X of the cerebellum and left precentral gyrus may contribute to the deterioration in WM after acute SD.

Availability of Data and Materials

The data presented in this study are available on request from the corresponding author.

Author Contributions

Investigation, methodology, drafting, reviewing and editing: ZYW, STF; investigation, methodology: SSZ, LRD; conception and design, supervision, methodology, reviewing and editing, funding acquisition: HXJ, YZN. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the Declaration of Helsinki, and informed consent was obtained from each enrolled patient prior to the study. The Ethics Committee of Beijing Anding Hospital, affiliated with Capital Medical University, approved the study protocol (Approved No: 202065FS-2, number of clinical registrations: ChiCTR2000039858).

Acknowledgment

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Conflict of Interest

The authors declare no conflict of interest.

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