Changes in delta and theta oscillations in the brain indicate dynamic switching of attention between internal and external processing

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ABSTRACT

When interacting with the complex and rapid change environment, human brains often face the challenge that not only abundant external, sensory information but also sophisticated internal information need to be processed in real time with limited cognitive resources. Attention shifts have been demonstrated as an effective approach to dynamically allocate the brain's processing power towards more relevant aspects of incoming sensory information, such as specific spatial locations, sensory modalities or features, etc. However, how the brain switches between external and internal attention has not been fully understood. In this work, 20 human subjects performed four different attention tasks, including visual, auditory, audio-visual and mental arithmetic, while scalp electroencephalogram (EEG) signals were recorded. With similar auditory and visual stimuli given simultaneously across all tasks, the dynamic switching of brain state between internal (mental arithmetic) and external (visual, auditory and audio-visual) attentions were studied. We found that the delta and theta oscillations exhibited increased power in a wide range of brain areas, especially in the frontal and occipital regions, during the mental arithmetic task. The changes in the delta and theta power were accompanied by enhanced functional connections (FCs) within the frontal area but reduced FCs between the frontal area and other regions. Such changes were frequency specific, as we didn't find the same trend for alpha oscillations. These results suggest that enhanced oscillatory activities of relatively lower frequencies across a wide range of brain areas, as well as associated reconfiguration of FCs, may be a feature of dynamic switching of attention towards internal processing versus the incoming sensory information.

CCS CONCEPTS

• **Applied computing**; • **Life and medical sciences**; • **Computational biology**; • **Biological networks**;

KEYWORDS

EEG, sensory information processing, functional connectivity, internal and external attention

ACM Reference Format:

Yuying Jiang, Haoran Zhang, and Shan Yu. 2021. Changes in delta and theta oscillations in the brain indicate dynamic switching of attention between internal and external processing. In *4th International Conference on Biometric Engineering and Applications (ICBEA '21), May 25–27, 2021, Taiyuan, China.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3476779.3476784

1 INTRODUCTION

We often face abundant incoming streams of both external, sensory as well as internal information during our interaction with the environment. In order to properly integrate the most relevant information at hand, attention is used to allocate the limited cognitive processing power across information coming in from different spatial locations, sensory modalities or features. Conceivably, a rapidly changing environment condition with different tasks would require the brain to flexibly shift attention so that each task can be fully concentrated in a dynamic way [1].

The underlying neural mechanisms of attentional shifts have been actively discussed in several aspects, especially in the processing of sensory information, e.g., spatial attention, cross-modality attention, attention shifts between features such as shape and color, etc. The spatial attention of auditory, visual, or multisensory stimuli have been found with significant lateralized activation on the opposite hemisphere of cued direction [2][3][4]. The cross-modality

ICBEA '21, May 25–27, 2021, Taiyuan, China

ACM ISBN 978-1-4503-8765-1/21/05…$15.00
https://doi.org/10.1145/3476779.3476784

attention has been found with a significant attention-related activation in the posterior, parietal and prefrontal cortices reflected by the blood-oxygen-level-dependent (BOLD) signals [2][5][6][7]. Similar activation effects have also been found using entrainment paradigm in electrophysiological studies [8][9][10].

Nonetheless, the attention shifts mentioned above only cover the manipulation effects of external attention on sensory processing, without taken into account that lots of internal information processing needs to be carried out at the same time and, therefore, also requires attention. For example, the internal attention could be set by a mental calculation task. The mental arithmetic task, in which the subject needs to add numbers continuously given an arbitrary start, mimics common cognitive tasks that require demanding internal processing. Previous studies have found such a task reliable activates the inferior frontal and anterior cingulate cortices [11][12]. Unlike the external attention shifts mentioned above, how the brain states dynamically switches between internal and external attention, especially when several sensory streams co-exist at the same time and requires a more sophisticated strategy of attentional switch, is not fully understood, which hinders a comprehensive understanding of the general mechanism underlying dynamic attentional shifts in more complex environments.

To address this issue, in the present study, subjects were asked to switch their attention among four tasks on a trial-by-trial basis, including the visual attention task, auditory attention task, visual and auditory dual-modality attention task, and the mental calculation task, while the EEG signals were recorded throughout the entire experiment. First, we examined how the local brain states modulated by these four attentional tasks can be reflected in neuronal oscillatory activities. In particular, we focused on the lower frequencies, including the delta, theta and alpha oscillations, which are often involved in attention [13]. Second, we investigated the EEG dynamics on the global brain network, using the functional connectivity (FC) as a measure, to reveal the signature of attentional-dependent reconfiguration of area-area interactions in the brain.

2 MATERIALS AND METHODS

2.1 Subjects

Twenty subjects (three females and 17 males, mean age: 25, age range: 21-28, all right-handed) participated in the study. All subjects reported normal hearing, normal or corrected-to-normal vision and no history of any neurological or psychiatric disorders. The study was approved by the institutional ethics committee, and all subjects provided informed consent for participation.

2.2 Stimuli and experimental design

The visual stimuli were presented as a large white circle that flicked at 39Hz frequency on the center of the screen (Alienware, 240Hz refresh rate), which was placed in frontal of the subjects. The rhythm of auditory stimuli was 40Hz, created by a square wave's amplitude modulation with a 10kHz tone lasting for 1ms in each cycle. The presentation of the stimuli was controlled by MATLAB (MathWorks, Natick, MA) using the Psychophysics Toolbox Version 3 (Brainard). In order to make sure that the subjects pay attention to the corresponding modality, we imbed specific cues in the visual and auditory stimuli of all tasks. As for the visual cues, a small black circle in the center of the large white circle would randomly turn red, with an average of 9 occurrences in each trial at intervals ranging from 0.5s to 2s. Auditory cues were transient beeps that appear randomly during the auditory stimuli, with the same occurring frequency and interval as the visual cues. Through the pre-experiment, we determined a series of subject-specific parameters, including the brightness of the visual cues and the volume of auditory cues for the latter formal experiment, with the selection criteria that the subjects could recognize the cues with ~80% accuracy. In each trial, the visual and auditory stimuli were presented simultaneously.

As shown in Figure 1A, there were four types of trials/tasks used, namely the visual attention trial, auditory attention trial, dual-attention trial, and the mental arithmetic trial. The mental arithmetic task requires internal attention, while the other tasks require different types of external attention. In the visual attention task, the subjects needed to press the visual button as soon as possible when they saw the visual cues, without responding to the sound cues. Correspondingly, in the auditory attention task, the subjects needed to press the auditory button as soon as possible while hearing the auditory cues, without responding to the visual cues. In the audio-visual dual-attention task, subjects needed to press the button as soon as they saw the visual cues or heard the auditory cues. In order to ensure that the total number of cues in each trial was the same, the number of visual and auditory cues were reduced to its half value in the audio-visual attention task. In the mental arithmetic task, the subjects did not need to press the button. Instead, at the beginning of each trial, a starting number between 10 and 40 was presented on the screen, and the subjects needed to accumulate a series of continuous natural numbers starting from this number until the end of the audio-visual stimulation. In order to fully receive the visual stimuli, we asked the subjects to always focus on the center of the screen, which was monitored by an experimenter in the real time through a camera recording the eye movements of the subjects.

Figure 1B shows the process of each trial. Firstly, the subjects pressed the button to start the trial. Next, the screen showed what the next task was, and if it was a mental arithmetic task, it showed the starting number at the same time. After 2 seconds, the visual and auditory stimuli were presented simultaneously, and subjects need to make proper responses according to the task. The presentation time of the stimuli was 20s. If it was a mental arithmetic task, the subjects were asked to report the results orally after the sensory stimulation were finished. The experiment was carried out in sessions, with 16 trials in each session, containing 4 trails for each task, presented in a random order. Each subject was required to complete three sessions.

2.3 EEG recording and preprocessing

The EEG data were recorded using the BrainAmp DC amplifier and 64 electrodes EasyCap (Brain Products GmbH, Gilching, Germany). The electrodes were placed according to the standard 10-20 system. AFz was used as ground and FCz was used as reference on the apex of nose. Vertical electrooculogram was recorded to monitor eye movement and blinks. The EEG signals were amplified and digitized at a sampling rate of 5000Hz (0.016~100Hz bandpass filtering), with the impedance of each electrode below 10kΩ. Data acquisition

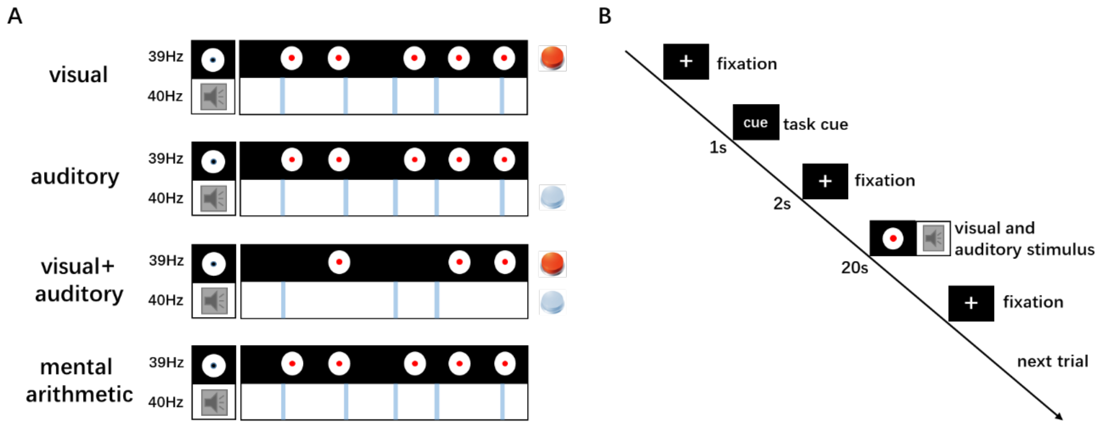

Figure 1: Illustration of the task (A) and the structure of the behavioral paradigm (B). Each trial was preceded by a cue telling the subject the nature of the current task, followed by a combination of visual and auditory stimuli. Subjects finished the corresponding key pressing reporting task or mental arithmetic task according to the requirements

was controlled through Brain Vision Recorder (version 1.03, Brain Products GmbH, Gilching, Germany).

EEG preprocessing were performed in Brain Vision Analyzer (version 2.0, Brain Products GmbH, Gilching, Germany). Raw EEG data were 1-100Hz band-pass filtered off-line with a notch filter at 50Hz. Eye movements and blinks were excluded using independent component analysis for each subject. Since we were interested in how brain activities changed between internal and external attention shifts, our subsequent analysis was based on EEG data within the 20-second periods after the onset of stimulus' presentation.

2.4 Power analyses

One electrode was used as eye movement signal, and hence this channel was excluded from the following analyses and in total we obtained 63-channel of preprocessed EEG data. All EEG analyses were carried out in MATLAB (MathWorks, Natick, MA) using the Fieldtrip toolbox and custom scripts. For each subject, power for frequencies from 1 to 13Hz was calculated for each trial under 4 different tasks using the function *ft_freqanalysis* implemented in the Fieldtrip toolbox. In line with previous studies, data were analyzed in 3 different frequency bands: delta (1–4Hz), theta (4–8Hz), and alpha (8–13Hz). The mean values across all trials for each subject was used for display and statistical analysis.

In order to identify the brain areas in which the EEG power during the mental arithmetic task was significantly different compared to other tasks, a paired t-test was used for each channel between the mental arithmetic task and the other three tasks. False discovery rate (FDR) correction for multiple comparisons was applied and the adjusted significance level was set at $p < 0.05$.

2.5 Functional connectivity analyses

In order to suppress spurious coherence caused by the volume conduction effect, we estimated the FC between pairs of electrodes through computing the imaginary part of the coherency (REF). FC analysis was also applied to the delta, theta, and alpha bands. Taken the delta band for example, for each subject, we first calculated the FC matrixes for each trial under 4 different tasks. Then, the mean FC matrixes for each task was calculated. Next, we subtracted the mean FC matrices of the other three tasks from that of the mental arithmetic task to obtain three difference matrices. Each difference matrix was then normalized by its maximum value. Finally, the three normalized difference matrices of 20 subjects were averaged to obtain three group difference summation matrices, which indicate the difference in the FC between the mental arithmetic task and the other three tasks in the corresponding frequency band.

To examine the spatial characteristics of the effects, we divided all electrodes into 7 groups (Left Frontal (LF): (Fpz, Fp1, AF3, AF7, Fz, F1, F3, F5, F7), Right Frontal (RF): (Fp2, AF4, AF8, F2, F4, F6, F8), Left Central (LC): (FC1, FC3, FC5, Cz, C1, C3, C5, CPz, CP1, CP3, CP5, Pz, P1, P3, P5), Right Central (RC): (FC2, FC4, FC6, C2, C4, C6, CP2, CP4, CP6, P2, P4, P6), Left Temporal (LT): (T7, P7, FT7, TP7, TP9, FT9), Right Temporal (RT): (T8, P8, FT8, TP8, TP10, FT10), Occipital (O): (Oz, O1, PO3, PO7, O2, PO4)) for statistical analysis. By visualizing the summation matrices described above, we looked for areas in the three frequency bands where the functional connections during the mental arithmetic task tended to increase or decrease compared with the other three tasks. Paired t-test between mental arithmetic task and the other three tasks was applied for the mean values in each entry of the matrices.

3 RESULTS

3.1 EEG power

The power of four frequency bands delta (1-4Hz), theta (4-8Hz), alpha (8-13) were analyzed under 4 tasks. At each frequency band, the mean value of mental arithmetic task of 20 subjects was compared with the mean value of other tasks. Figure 2A is topographic maps of the difference. For lower frequency bands, mental arithmetic tasks had higher power than other three tasks in a wide area of the brain. Specifically, for the delta and theta bands, the power was higher in frontal and occipital regions. For the alpha band, the power in the occipital area was higher during the mental

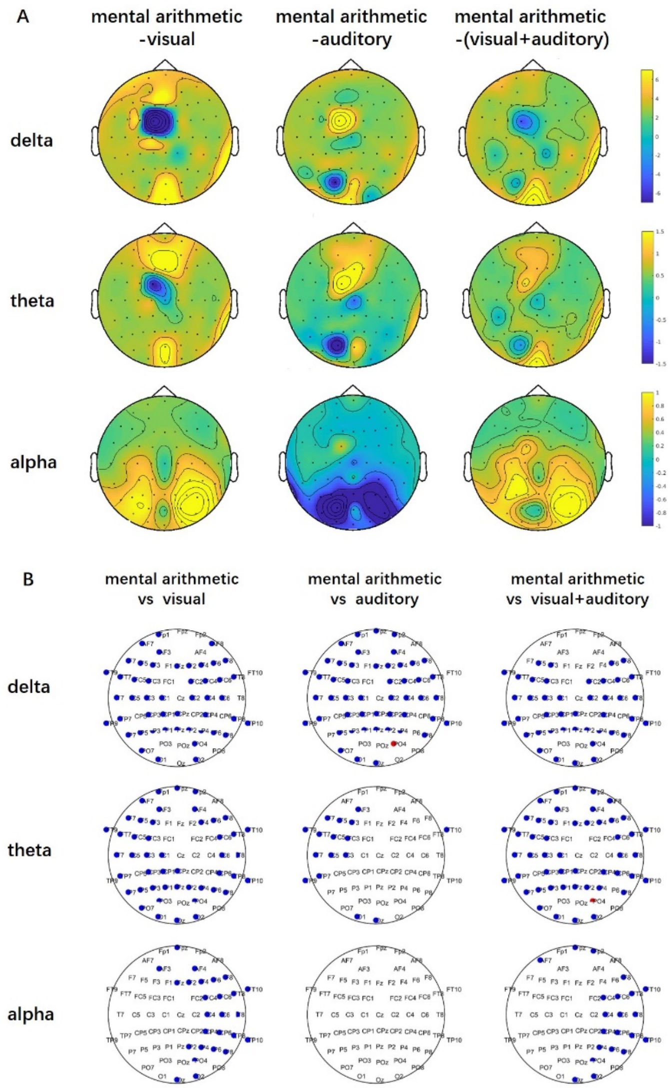

Figure 2: Power topographic maps and statistical results. A, power topographic maps under different conditions in three frequency bands. B, In the three frequency bands, the power of the mental arithmetic task was compared with the power of the other three tasks respectively, using the paired t-test. The blue dots indicated that the power of the mental arithmetic task was significantly higher than that of the other tasks. The red dots indicated that the power of the mental arithmetic task was significantly lower than that of other tasks.

arithmetic tasks compared to the visual and audio-visual tasks, but lower compared to the auditory task.

Figure 2B showed the results of statistical analysis. It revealed that in the delta band, the power in most channels in the mental arithmetic task were significantly higher ($p < 0.05$) than the other three tasks. In the theta band, the power in most channels in the mental arithmetic task were significantly higher than in the visual and audio-visual tasks. Compared with the auditory task, the mental arithmetic task had significantly higher theta band power in the temporal and occipital areas. For the alpha band, only when comparing with visual and audio-visual tasks, the right hemisphere exhibited significantly increased power during the mental arithmetic task.

3.2 Functional connectivity

To examine the changes in FCs, the imaginary part of the coherency of the delta, theta, and alpha bands were analyzed during the 4 tasks. Figure 3 showed the group-averaged differences in FC of 20 subjects between the task of mental arithmetic and the other three tasks

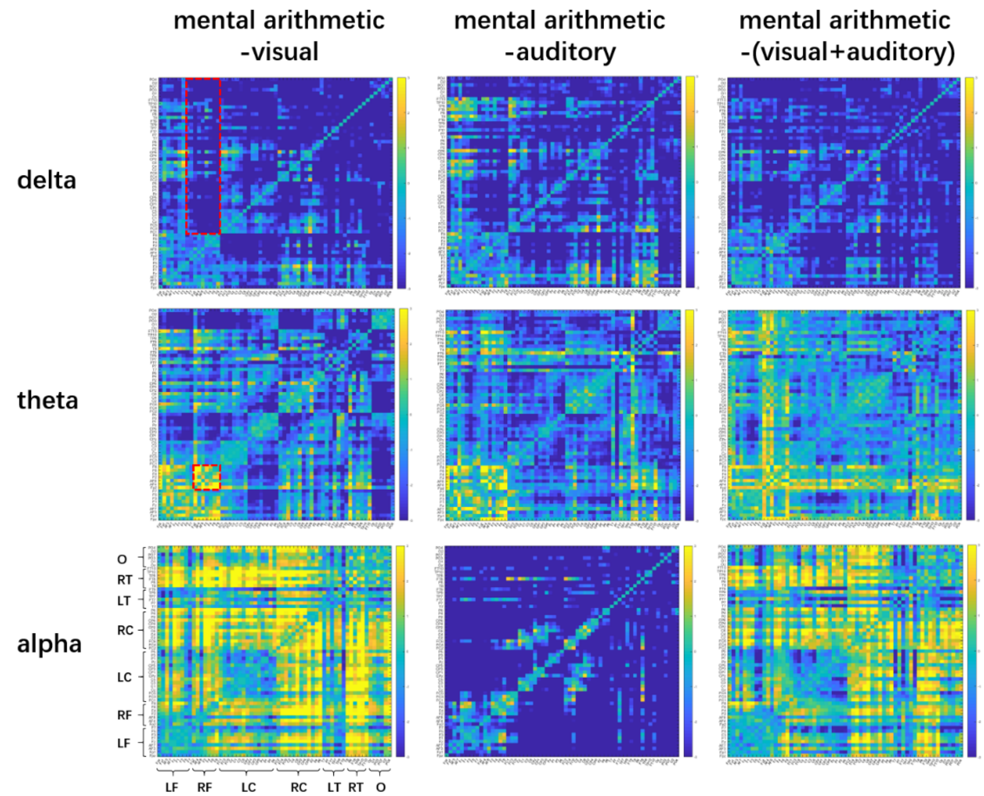

Figure 3: The results of the FC matrices of the mental arithmetic task compared with that of the other tasks in three frequency bands. The area in the red dotted box was chosen for subsequent statistical analysis.

at different frequency bands. It could be seen that the overall FCs during the mental arithmetic task were weaker at the delta band but stronger at the theta band. To examine the changes in FCs more closely, we identified two sets, i.e., the FCs within the right frontal (LF) areas in the theta band and the FCs between RF and other areas in the delta band that showed pronounced changes during the mental arithmetic task compared with the other three tasks.

Figure 4 showed the result of paired t-test for these two sets of FCs in different tasks in each area respectively. We found that the FC between the right frontal area and the other areas of the brain was indeed significantly weaker in the mental arithmetic task than in the other three tasks in the delta band (Fig. 4a). At the same time, FCs within the right frontal area were significantly stronger in the mental arithmetic task than in the other three tasks (Fig. 4b).

4 DISCUSSION

4.1 Enhanced delta and theta oscillations during internal attention

In the present study, when subjects shifted their attentions from external auditory and visual stimuli to the numerical calculation, we found that low-frequency components, including the delta and theta bands, in EEG showed a significant enhancement in power, especially in the frontal and occipital areas during the mental arithmetic task.

Mental math calculation tasks were often used to draw subjects' internal attention, which was associated with delta and theta power increases. Our result that delta power increased in mental arithmetic was consistent with previous studies [14][15]. It is also known that visual, memory and executive resources are involved in solving the problems of numerical calculation [14][16][17][18]. Previous findings have demonstrated the enhancement of theta power during numerical calculation, working memory and the maintenance of goal states [13][17][19][20], which is consistent with the current findings that during the mental arithmetic task, the theta power was enhanced, especially in the frontal areas. Moreover, increased occipital theta activation has been responsible for controlling cognitive demands [21]. Identifying and processing stimuli is also associated with occipital activation in the theta band [22].

Here we showed that the attention switch to a task requiring internal attention resulted in the delta and theta power enhancement. However, it would be very informative for further studies to investigate if such effects are task-specific with the mental calculation progress, or they reflect a general feature of internal attention. Some evidence showed that it is the sustained attention during mental arithmetic that was associated with frontal theta oscillations [19]. Also, the low frequency signatures augmentation could be induced by the shift process with a certain time window from outside attention to inside one, rather than the effect of internal

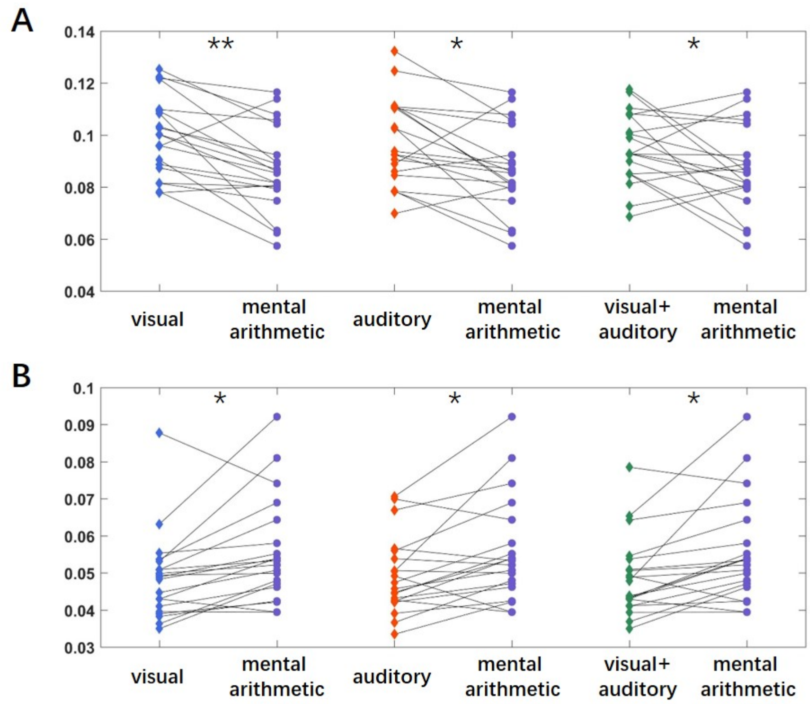

Figure 4: Statistical results of functional connections across all 20 subjects. A, in the delta frequency band, the results of the paired t-test between the right frontal lobe and the other areas of the brain except the frontal lobe. B, in the theta frequency band, the results of the paired t-test within the right frontal lobe. * denotes $p < 0.05$, ** denotes $p < 0.001$.

attention itself. For example, the increased occipital theta activation was only observed in the early stages of mental calculation [23]. Thus, although the present results provide important evidence of enhanced low frequencies components in internal processing, it awaits future experiment to better delineate the effects of specific internal processing task, level of sustained attention, and the attentional shift.

4.2 The role of alpha oscillation in attention switching

Previous studies on cross-modal and spatially selective attention have yielded many results about the alpha band. Alpha power in the parietal-occipital area robustly decodes the attended spatial location [24][25]. In a previous study, we also found enhanced alpha activity at parietal-occipital area in the auditory compared to the visual attentive state in cross-modal selective attention [26]. But in the current study, we did not find consistent results of changes in the alpha band between the mental arithmetic task and the other three tasks, in terms of both power and FC. This suggests that the mechanism for switching between internal and external attention might be different from the mechanism for selective attention between different external stimuli.

4.3 A possible mixed mechanism for internal attention: information gating and enhanced utilization of cognitive resources

In previous fMRI studies using mental arithmetic tasks, activation of the prefrontal area was reported [17], suggesting an important role of this area to carry out the mental arithmetic task. Here we found increased FC within the frontal area itself but decreased FCs between the frontal area and other brain regions (Fig.4). These results suggest the possibility that mental arithmetic task requires more intense processing within the prefrontal cortex (PFC) and, at the same time, possible gating of distracting sensory information to be routed to the PFC.

5 CONCLUSION

In this work, we designed four attention tasks of visual, auditory, audio-visual and mental arithmetic along with simultaneous presentation of auditory and visual stimuli to study the brain activity changes during the transition between internal and external attention. We found that an enhancement in the low-frequency EEG power with internal attention, particularly in the frontal and occipital lobes in the theta and the delta bands. Meanwhile, there was a significant increase in FCs within the right frontal area in the theta band, but a decrease in the FCs between the right frontal area and other brain regions in the delta band. A comparison to the result of the alpha band showed that these changes only occurred at lower frequencies. These results suggest that delta and theta oscillations might be important in mediating the attentional switch from external, sensory stimuli to internal processing, which can be manifested in both the delta and theta power of local brain areas and more global interaction patterns among spatially separated areas.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Yijun Wang and Dr. Zhen Liang and Li Zheng for technical assistance during the early stage of this work. This work was supported by the National Key Research and Development Program of China (2017YFA0105203), the Strategic Priority Research Program of the Chinese Academy of Sciences (CAS) (XDB32040200), and the Beijing Advanced Discipline Fund.

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