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Original Paper

Activity Status in Prefrontal Brain Regions Associated with Cognitive Reappraisal and Response Inhibition

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Abstract

Cognitive reappraisal and response inhibition are the two most important strategies for emotion regulation, but the related neural mechanisms are poorly understood. In this study, Functional Near-infrared Spectroscopy (fNIRS) was used to investigate the activation in regions of the prefrontal cortex of 33 undergraduate students while they were performing cognitive reappraisal and response inhibition tasks. We measured the changes of haemoglobin in six brain regions of the prefrontal cortex for the two emotional regulation tasks. We found that the activation levels of the left ventrolateral prefrontal cortex (oxyhemoglobin level, HbO) and frontopolar area (deoxyhemoglobin level, HbR) were significantly different during cognitive reappraisal and response inhibition tasks. More generally, we found that the left ventrolateral prefrontal and frontal pole regions may play key roles in cognitive reappraisal and response inhibition, but the specific physiological mechanisms involved need to be further investigated.

Keywords

functional near-infrared spectroscopy, cognitive reappraisal, response inhibition, left ventrolateral prefrontal cortex, frontopolar area

1. Introduction

Emotion regulation refers to the regulation process of emotion occurrence, experience and expression. Cognitive reappraisal (reinterpreting emotion-eliciting scenarios in a more positive light) and response inhibition (inhibition of the emotion-expressive behaviour) are the most researched emotion regulation strategies (McRae & Gross, 2020). Cognitive reappraisal takes place before emotion response and is considered antecedent-focused, while response inhibition takes place after emotion response and only influences the final response stage of emotion generation. To better understand the neurobiological basis of emotion regulation, an increasing number of studies have introduced brain functional imaging techniques in recent years. Previous studies have found that the brain regions associated with these two emotion regulation strategies include the amygdala, insula, ventral striatum and prefrontal lobe (Ochsner et al., 2015; Buhle et al., 2014). However, only a few previous studies focused on the role of distinct regions of the prefrontal lobe in these two emotional regulation strategies, and the results are very inconsistent (Turnbull & Salas, 2021; Andrea et al., 2014). Given the different mechanisms between cognitive reappraisal and response inhibition, we expected significant differences in the neurobiological basis of the two strategies (Seixas et al., 2021).

To address this hypothesis, we used Functional Near-infrared Spectroscopy (fNIRS), which is a very promising optical, non-invasive neuroimaging technique that utilises near-infrared light (650-1000 nm) to monitor and detect the concentration changes of oxygenated (HbO) and deoxygenated (HbR) haemoglobin in the brain tissue following neuronal activation. In recent years, fNIRS has been increasingly utilised in research on psychological mechanisms because of its several advantages over other neuroimaging techniques, including flexibility, portability, anti-interference ability, low cost and wide application range (Expert Consensus on Clinical Application of Near-Infrared Brain Functional Imaging Technology Writing Group, 2021; Chen et al., 2020).

In this study, we used fNIRS to explore the changes in brain neural activity associated with cognitive reappraisal and response inhibition and speculated about the neuropsychological mechanism underlying the two emotion regulation strategies.

2. Methods

2.1 Subjects

A total of 24 undergraduate students (5 males and 19 females, aged 18-22 years) were recruited at Hangzhou Normal University, Hangzhou, from Sep 2023 to Sep 2024. All subjects were right-handed and had normal vision and no hearing or communication impairments. We excluded students with brain

damage, neurological disorders, or any mental disorder reported in their personal history and anamnesis. A consent procedure approved by the Scientific Research Ethics Committee of Hangzhou Normal University was conducted. All subjects volunteered to participate in the study and provided written informed consent.

2.2 Psychological Experiments

For emotional stress material, 50 negative affective pictures (Valence Mean < 2.0, Arousal Mean > 6.0) were selected from the International Affective Picture System (Lang et al., 1995). Each picture was resampled and converted into 260×300 TIF files with uniform brightness and consistent contrast. In reference to previous studies, the experiment was conducted in blocks of three kinds: block A, to reappraise the meaning of the picture as a virtual scene; block B, to inhibit the emotional reactions induced by the picture and block C, to merely view the picture but not regulate any feelings, thoughts and emotional experiences (Boehme et al., 2019). All instructions and stimuli were presented on a computer screen of 1280×1024 pixel resolution and 60 Hz refresh rate. For each block, an instruction appeared first at the centre of the screen, the subjects pressed the button to start the experiment after they fully understood the instruction, a black fixation point presented at the centre of the screen for 300 ms. Subsequently, five pictures were presented successively at the screen's centre for 3000 ms each (15s total), and the participants were required to focus on the pictures, using, according to the instruction, one of the emotion regulation strategies (for block A or B) or simply viewing the pictures (for block C). At the end of the block, the participants were asked to rate their emotional experience on a 1-9 scale (from 1=very pleasant to 9=very unpleasant, with 5=neutral) within 5000 ms. The time course of a single trial is depicted in Figure 1.

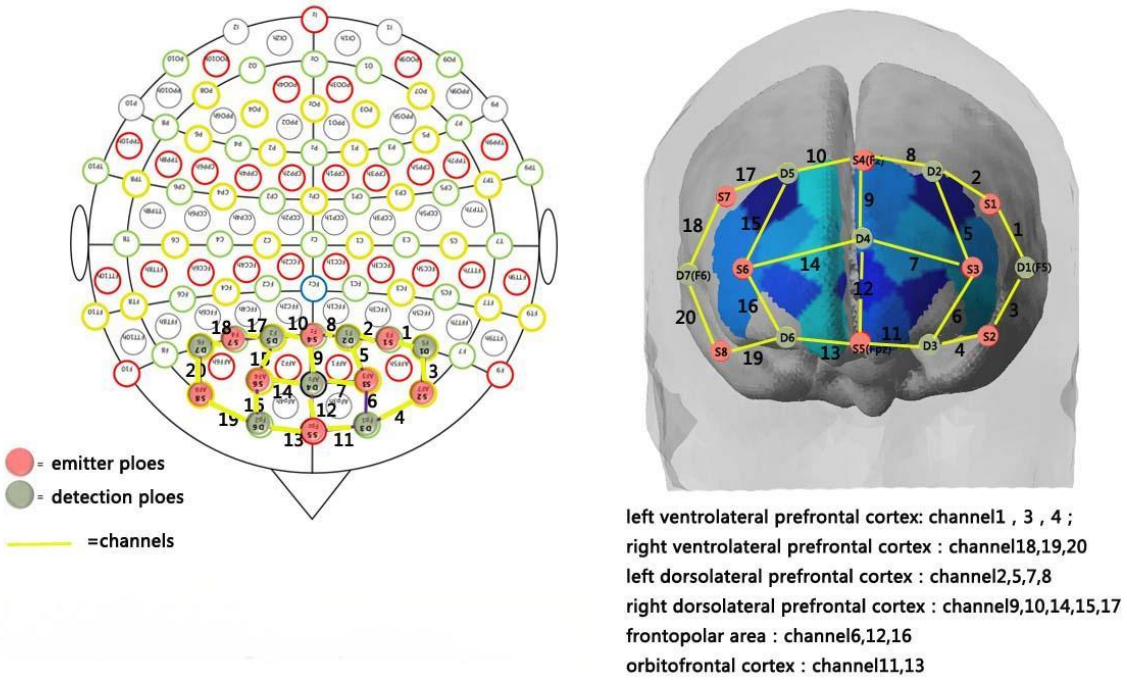

Figure 1. The Position of Emitter Ploes, Detection Ploes, Channels, and Brain Regions of Prefrontal Cortex

2.3 fNIRS Data Acquisition and Pre-processing

fNIRS data were acquired by using the portable NIR brain imaging system, consisting of seven detection poles and eight dual-wavelength (785nm and 830nm) emitter ploes, with a 3.0 cm separation between the poles, constituting 20 channels. We used a sampling frequency of 7.8125 Hz (Figure 1). The point on the midline in the frontopolar area was determined by the international 10-20 electrode configuration method. The fNIRS channel positions were aligned with the Montreal Neurological Institute spatial coordinates by the probabilistic registration method to obtain a correspondence with the six prefrontal brain regions (Figure 1), including regions of the left and right ventrolateral prefrontal cortex (VLPFC), the left and right dorsolateral prefrontal cortex (DLPFC), the frontopolar area and the orbitofrontal cortex. The recording room was kept quiet during data acquisition.

fNIRS data were pre-processed using the nirsLAB software accompanying the instrument. After band-pass filtering to remove baseline drift, the optical data were converted to oxyhemoglobin concentration (HbO) and deoxyhemoglobin concentration (HbR) based on a formula using a modified Beer-Lambert law. Because there is some controversy regarding the consistency of HbO and HbR metrics on neuronal activity, we analysed both HbO and HbR (Expert Consensus on Clinical Application of Near-Infrared Brain Functional Imaging Technology Writing Group, 2021). The variations in HbO and HbR concentrations were derived by subtracting the baseline concentration (corresponding to the quiet rest period with eyes closed) from the concentration of HbO and HbR

during the execution of the tasks and used as an indicator of changes in brain activity in each brain region.

2.4 Statistical Analyses

SPSS 26.0 was used for statistical analyses. After testing for normality, data conforming to a normal distribution were analysed by using the paired-samples t-test for a difference from baseline for both tasks. Data not conforming to a normal distribution were analysed by using the non-parametric paired-samples rank sum tests. Samples with missing entries were amended with the sample median. Significance levels were set at $p < 0.05$ for all two-sided tests.

3. Results

3.1 Analysis of Changes in Oxyhemoglobin Concentrations during Cognitive Reappraisal and Response Inhibition Tasks

HbO concentration changes in six brain regions measured while subjects performed the two tasks were subjected to paired comparison with baseline. This analysis revealed that there were significant differences in the left VLPFC ($t = -2.637$, $p<0.014$) in both tasks but none in the other five brain regions in either task (Figure2 and Table1). These results indicated that the activation of the left VLPFC was significantly different during both the cognitive reappraisal and the response inhibition tasks.

Table 1. The Oxyhemoglobin Concentrations for Cognitive Reappraisal and Response Inhibition

	cognitive reappraisal	**response inhibition**		
	Mean±SE	*Mean±SE*	*t*	*p*
left VLPFC*	0.00004991±0.00026339	0.00051312±0.00024788	-2.637	0.014
right VLPFC	-0.00000779±0.00027241	0.00008002±0.00028132	-0.38	0.708
left DLPFC	-0.00019539±0.0002833	-0.00001764±0.00025214	-1.25	0.223
right DLPFC	0.00006144±0.00032623	0.00019008±0.00033655	-0.698	0.492
frontopolar	0.00019919±0.0002823	0.00022269±0.0002612	-0.143	0.887
orbitofrontal cortex	0.00004106±0.00040984	0.00003535±0.00032912	0.024	0.981

**: P <0.05; **: p <0.01*

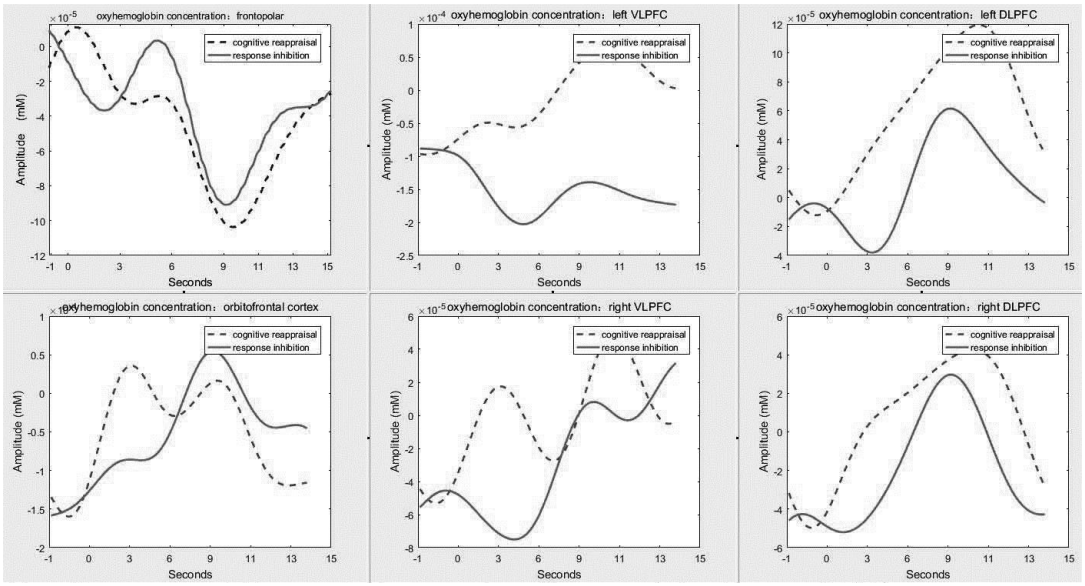

Figure 2. The Oxyhemoglobin Concentration Curve of Cognitive Reappraisal and Response Inhibition

3.2 Analysis of Changes in Deoxyhemoglobin Concentrations during Cognitive Reappraisal and Response Inhibition Tasks

A similar analysis of HbR concentrations revealed a significant difference in the frontopolar area ($t = 2.783$, $p < 0.010$) in both tasks, while there was no significant difference in the other five brain regions in either task (Figure 3 and Table 2). These results suggest that activation of the frontopolar area was significantly different during the performance of both the cognitive reappraisal and response inhibition tasks.

Table 2. The Deoxyhemoglobin Concentrations of Cognitive Reappraisal and Response Inhibition

	cognitive reappraisal	**response inhibition**		
	Mean ±SE	*Mean ±SE*	*t*	*p*
left VLPFC	0.00003932 ±0.00013627	-0.00018323 ±0.00014027	0.905	0.375
right VLPFC	0.00001242 ±0.00005642	-0.00004403 ±0.00005543	0.84	0.409
left DLPFC	0.00004702 ±0.0000717	0.00000375 ±0.00005943	0.931	0.361
right DLPFC	0.00001222 ±0.00008124	-0.00001876 ±0.00007281	0.421	0.678
frontopolar*	0.00009941 ±0.0000658	-0.00000877 ±0.00007024	2.783	0.010
orbitofrontal cortex	0.00012443 ±0.00009344	0.00000685 ±0.00004866	1.862	0.075

**: P <0.05 **: p <0.01*

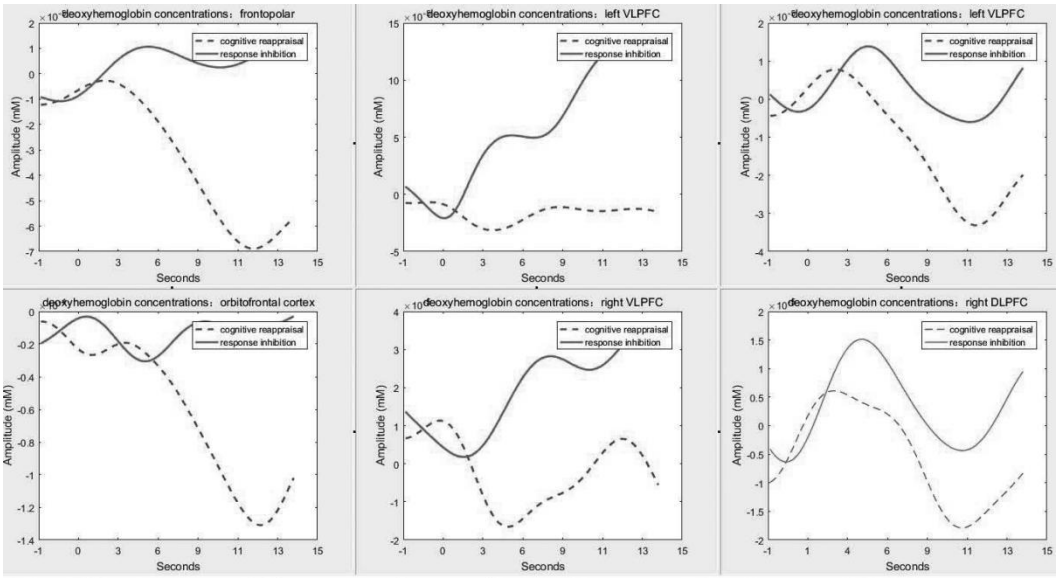

Figure 3. The Deoxyhemoglobin Concentration Curve for Cognitive Reappraisal and Response Inhibition

4. Discussion

Cognitive reappraisal and response inhibition are the two most important emotion regulation strategies and involve the prefrontal cortex. This study used fNIRS to explore which areas of the prefrontal cortex were specifically involved in these two strategies. While fNIRS detection has an admittedly limited depth in the cerebral cortex, it is most suitable for studying the real-time variation of activity in the prefrontal cortex. We measured the blood oxygen data from six prefrontal cortex areas in subjects who performed tasks using cognitive reappraisal or response inhibition strategies to regulate emotions, and the brain activation in each region during each task was inferred from the blood flow changes in response to blood oxygen changes.

Our results show significant differences in HbO concentration changes in the left VLPFC when subjects regulate their emotions by means of cognitive reappraisal or response inhibition, suggesting that the left prefrontal VLPFC plays a key role in both emotion regulation strategies. The VLPFC, located in the ventral front of the frontal lobe, is divided into two symmetrical regions, which are involved in various cognitive and emotional functions, such as language processing, facial information, gesture information and emotional regulation. However, the results of previous studies of the effects of the left VLPFC on individual executive emotional and behavioural inhibition functions were inconsistent. Sliver et al. showed that the left VLPFC played an important role in the activation of the amygdala during cognitive reappraisal, but the activation was greatly affected by age (Silvers et al., 2017). Goldin et al., in an MRI study on response inhibition regulation strategy, showed that the left VLPFC was activated when subjects were emotionally inhibited (Goldin et al., 2008). The results of this study suggest that the difference in the changes in brain neural activity in the left VLPFC may be

the vital difference in the brain mechanisms involved in cognitive reappraisal or response inhibition.

We also found significant differences in HbR concentration changes in the frontopolar region of the prefrontal lobe when subjects performed cognitive reappraisal or response inhibition tasks. We speculated that the frontopolar region may play a key role in the execution step of the two emotion regulation strategies. The frontopolar cortex also known as Brodmann Area 10, is the largest brain areas of the frontal lobe (Peng et al., 2018). Several studies have reported that the frontopolar brain region is associated with psychological processes involved in processing reward information, negative emotions and self-cognition (Tashjian & Galván, 2021; Ziaei et al., 2019; Miyamoto et al., 2018; Mansouri et al., 2017). Very few previous studies investigated the role of the frontopolar region in emotion regulation. Our results suggest that the functions of the frontopolar region include cognitive reappraisal and response inhibition, but this needs to be further explored.

We highlight that we analysed both HbO and HbR changes in prefrontal brain regions, and the two analyses yielded results that appear inconsistent. The left VLPFC showed significant differences in HbO changes during the execution of the two tasks, but the frontal polar regions showed significant differences only in HbR changes. This is significant because most of the previous fNIRS studies analysed only one of the two types of haemoglobin data. Importantly, other studies have also demonstrated that the changes of HbO and HbR during brain activation were inconsistent and could even have large differences (Chen et al., 2020). While several parallel MRI and fNIRS studies have shown that only the variations in HbR levels captured by fNIRS measurements were positively related to brain region activation (Maggioni et al., 2015; Wijeakumar et al., 2017). There are also several other reports that only HbO level is significantly correlated with brain region activation (Cui et al., 2011). Our results also suggest that the changes in HbO and HbR are inconsistent during brain area activation and even suggest the involvement of different physiological mechanisms.

Overall, ours is the first study to use fNIRS to explore the neurophysiological mechanisms of cognitive reappraisal and response inhibition, two of the most frequently used emotion regulation strategies. Due to the insufficient sample size and the lack of control for the sex ratio of the subjects, the findings of this study, such as the distinct roles attributed to the left VLPFC and frontopolar regions in the two emotion regulation processes, and the specific biological basis of the HbO and HbR signals deserve further investigation.

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Author contributions

Dai Han, Yufei Zhao and Yi Wang designed and managed the research data selection and analysis. Yufei Zhao and Kaiyuan Zhu wrote the first draft of the manuscript. All authors contributed to and gave approved the final manuscript and agree to be accountable for all aspects of the work.

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