2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Negative affective processing is associated with cognitive control in early childhood: An fNIRS study *

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Abstract— **The association between emotion and cognition has recently gathered interest in the field of cognitive neuroscience. However, the neural mechanism of negative emotion processing and its association with cognitive control in early childhood remains unclear. In the present study, we compared the processing of three emotions (i.e., negative, neutral, and positive emotions) and investigated the association between negative emotion processing and cognitive control in children aged 4-6 years (N = 43). Results indicated that children revealed greater brain activation when processing negative emotions than processing neutral and positive emotions. We also found a significant negative association between brain activation during negative emotion processing and reaction times of cognitive control, which represented children with better cognitive control evoked higher brain activation when processing negative emotions. The current study proposes a neural mechanism underlying emotion processing and provides important insights into the risk and future behavioral outcomes of potential psychological disorders.**

I. Introduction

Affective processing has been found to change rapidly during early childhood. However, the neurobiological basis of emotional processing in early childhood is not well understood. Affective processing refers to a complex psychophysiological function, which comprises the detection of emotional cues through different sensory modalities, the integration of those inputs into an affective experience, and the execution of a behavioral response to the emotional stimuli [1]. It has been reported that emotional ability is significant in the early years' development. Specifically, affective processing is associated with later emotional functioning. School-aged children with attention deficit hyperactivity disorder have impaired recognition of emotional expression compared to typically developing children [2]. Individuals with social anxiety disorder show aberrant sustained emotion processing [3]. Moreover, a longitudinal study found that shyness in mid-to-late childhood predicted higher levels of anxiety and depression symptoms in early adolescence [4] impaired facial emotional processing has been a stable feature of schizophrenia [5]. Thus, emotional recognition and processing are fundamental to healthy social and emotional development, better understanding and awareness of negative affective processing during the early years of childhood may provide insight into ways of preventing the development of psychopathological conditions.

Previous research found that a close connection between affective processing and cognitive ability, especially in the early critical period of emotional and cognitive development [6]. Children between the age of 3-6 years old is a significant period of emotional development, cognitive and verbal abilities make remarkable noteworthy achievements in the development of children's emotional understanding. Studies indicated that children who exhibit better cognitive ability have a higher understanding of emotional understanding [7]. Prior work also demonstrated that the processing of emotional information interferes with cognitive performance [8]. For instance, Öhman et al. (2001) suggested that negative emotion is detected more efficiently than neutral information [9]. Consistent with this finding, it has been shown that healthy adults with more anxiety traits tend to show a negative affective bias of attention that may reflect reduced executive control [10]. Nevertheless, functional neuroimaging studies have also provided evidence on the association between emotion processing and cognitive ability. A study in typically developing boys found negative emotion modulates prefrontal cortex activity during a working memory task, specifically, angry faces elicited a greater increase activity of the right hemisphere [11]. Functional magnetic resonance imaging (fMRI) studies have revealed that in switch trials of the cognitive control task, the activation of the anterior cingulate cortex (ACC) significantly decreased in the positive condition and increased in the negative condition compared with the neutral condition [12]. More recently, a study on the neural bases of how positive emotions affect cognitive control indicated that, compared with the neutral condition, switch cognitive trials costs significantly decreased during the positive emotional condition and increased during the negative emotional condition [6].

The above studies suggest that emotional and cognitive systems are closely related, and negative emotion processing requires more prefrontal activity. However, these studies were focused on adults or adolescents, it is not clear whether cognitive ability has an effect on emotional processing in the critical period of children's emotional development. Optical techniques, such as functional near-infrared spectroscopy (fNIRS) have made it easy to measure hemodynamic changes in cortical regions. fNIRS is a noninvasive spectroscopic method that probes the changes in levels of Oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) over time while allowing the light body and head movements that could be a reliable tool to measure brain activation during emotional processing [13]. Thus, fNIRS was used to record brain

* Research supported by grants from the National Natural Science Foundation of China [Grant Numbers: 6550180027].

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activity during a combined emotional attentional task to evaluate brain activation differences among negative, positive, and neutral emotional processing, and assess the association between negative emotion processing and cognitive control in younger samples.

II. METHOD

A. Participants and Procedure

Fifty healthy children aged 4 to 6 years old were recruited totally. Seven children were excluded (N = 3 data loss due to technical problems, poor sensor contact, excessive movement artifacts; and N = 4 refusal to participate), which resulted in 43 participants (4.837 ± 0.748 years, 23 boys) with sufficient quality fNIRS data and behavioral data. All study procedures were approved by the Institutional Review Board at Southeast University. Written informed consent was obtained from all caregivers and oral consent was obtained from all children. Children were recruited from a suburban area of Nanjing City, China, through advertising in a childcare facility. Children were eligible to participate in this study if they did not have a history of a neurological disorder, loss of consciousness, or sensory impairments, autism spectrum disorder, or an intellectual disability. Each child received an age-appropriate toy after completing the experiment.

B. Intelligence assessment and behavioral task

The intelligence of children was measured using the Combined Raven's Test (CRT) [14] before fNIRS acquisition. We included Raven's Colored Progressive Matrices (14.44 ± 5.92) and Raven's Standard Progressive Matrices (20.83 ± 6.87). A modified behavior game called the Real Animal Size Test [15] was used to assess the cognitive control in children. The stimuli were pairs of cartoon animals that were presented on a laptop with a white background following an auditory cue. The child was seated at a table and instructed to identify the animal that was either visually larger (picture game) or larger in real life (animal game) by pressing on the left or right game button as quickly and as accurately as possible (there was no limit to response time). The stimuli were selected from three small animals (ant, mouse, and duck) and three large animals (cow, bear, and elephant), and one of the two animals presented side by side was visually larger than the other (side counterbalanced across trials). The task including congruent and incongruent trials, and three phases: control phase, inhibition phase, and switching phase. In the current study, we focused on the reaction times and accuracy of the switch phase only as the switch phase is more of an assessment of cognitive control.

C. Experimental task

A combined emotional attentional task (Fig.1(A)) was conducted to explore PFC activation while preschoolers processed three types of emotions (positive, neutral, and negative). There are five emotional trials: sad, angry, fear, neutral, and happy. The experiment included 3 blocks with each emotion type repeated 3 times and each block including 6 trials. For the analysis, we averaged sad, angry, and disgust trials for the negative emotion condition. The emotional stimuli were affective faces of a female neuroscience graduate student who created formal affective stimuli based on the affective faces from the Mindreading database [16]. Briefly, the child was seat at a table with a laptop placed in front of him/her. Each child has received the task instruction and carried out a practice session to ensure that the child had understood the task. An attention cue was displayed to instruct the child to start the task. The child was instructed to follow the partner's gaze (600 ms) towards the left or right by pressing the left (red) or right (blue) game button as quickly and as accurately as possible (with a maximum time limit of 2000 ms). The child then received feedback on whether they had correctly responded (feedback for a correct response was a tick mark beside the last stimuli displayed, whereas for an incorrect response, a picture that the partner displays body language "no", i.e., crossed arms.). The task was presented on a 14-inch computer screen (resolution of 1024 × 768) with a white background.

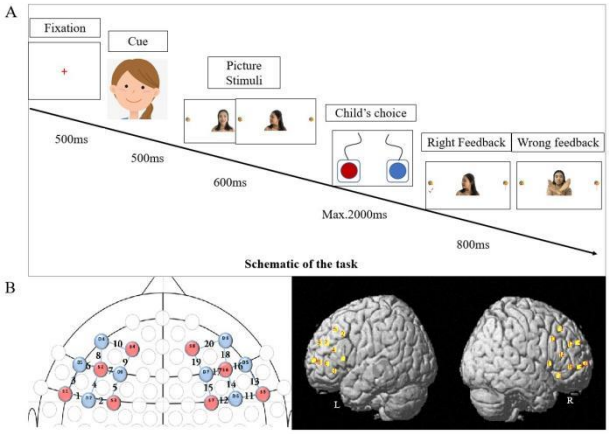

Figure 1(A). Schematic of the combined emotional attentional task (B). 2d and 3d map of source and detector optode placement.

D. fNIRS system

The experimental task was presented using the E-prime stimulation presentation software (Psychology Software Tools Inc., Pittsburgh, USA, Version 1.0). A NIRSport 8 × 8 optical Topography system (NIRx Medical Technology LLC, Glen Head, NY, USA) was used to record HbO and HbR concentration changes during the experimental task. The blood flow of the PFC was recorded in each child using the NIRx star software. The channel montage customized for this study included 20 channels that covered the bilateral dorsolateral prefrontal cortex (DLPFC), inferior frontal gyrus (IFG), and middle frontal gyrus (MFG). Sources were placed at AF3, F5, FC3, FT7 (left), AF4, F6, FC4, FT8, and detectors were placed at AF7, F7, F3, FC5, AF8, F8, F4, FC6, with a distance of 2.5 cm between optodes, based on a 10-10 transcranial positioning system. The absorption of near-infrared light was operated at wavelengths of 630 mm and 850 mm with a 7.81 Hz sampling rate. Channel and optode arrangements are depicted in Fig.1(B).

E. FNIRS data preprocessing and analysis

FNIRS data was pre-processed using Homer2, a MATLAB-based (The MathWorks, Inc., Natick, MA, USA) toolbox [17]. Intensity (raw data) was first converted into an optical density measurement and then corrected for motion artifacts using the channel artifact detection method (hmrMotionArtifactByChannel) and spline interpolation (hmrMotionCorrectSpline) [18]. If there were signal changes

that were greater than the threshold of 50 standard deviations or amplifier class of 5 within 0.5 s, then a segment of data around that time point was marked as a motion artifact. These artificial signal changes were corrected with a spline interpolation set to 0.99 parameters. The data were then band-pass filtered (0.01-0.2 Hz) to remove physiological noise and drift. Finally, the filtered data were converted into concentration units using the modified Beer-Lambert law [19]. The window of the hemodynamic response function (HRF) was maximal 11-21 s post-run onset for the combined emotional attentional task and was determined by visual inspection to include the peak of the HRF in each array, and this was used to calculate Oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) changes during the two tasks. Here, we report HbO using MATLAB mapping because it has been reported to be more sensitive to changes in regional cerebral blood flow [15]. The differences in activation and reaction times between the three emotions were determined using a mixed-analysis of variance (ANOVA) in SPSS Version 25 (IBM Corporation, NY, USA). A correlation analysis between behavior data of cognitive control and brain activation of the emotional task was brought to evaluate whether cognitive development has an effect on emotional processing.

III. Results

A paired t-test revealed a longer reaction time to negative emotions than to positive emotions ($t = 2.389$, $p = 0.022$) in the attentional task. Neutral emotions also showed a significantly longer reaction time than positive ($t = 4.079$, $p < 0.01$) and negative emotion ($t = 2.998$, $p = 0.005$). There was no significant difference in reaction times of negative and neutral emotions. Additionally, a significant association among the reaction times of the three conditions has been found: the reaction time of attentional task with negative emotions was significantly correlated with those of positive ($r = 0.544$, $p < 0.01$) and neutral emotions ($r = 0.346$, $p = 0.026$). Besides, there was no significant difference and association between the accuracy of the three emotion conditions (p's >0.05).

A repeated measures ANOVA with the emotion conditions as the within-subjects factor showed a significant main effect of emotion in CH5 ($F = 7.4$, $p = 0.011$), CH14 ($F = 5.973$, $p = 0.017$), CH15 ($F = 9.586$, $p = 0.003$), CH16 ($F = 6.17$, $p = 0.017$), CH17 ($F = 9.926$, $p = 0.004$), CH18 ($F = 16.689$, $p < 0.001$), CH19 ($F = 6.115$, $p = 0.017$), CH20 ($F = 12.714$, $p = 0.003$), which covered bilateral DLPFC and MFG and the right IFG (Fig 2.). Post-hoc tests revealed that emotional task with negative emotions evoked significantly higher brain activation than with positive emotions in CH5 ($p = 0.035$), CH14 ($p = 0.008$), CH15 ($p = 0.0014$), CH17 ($p = 0.014$), CH18 ($p = 0.0005$), CH19 ($p = 0.039$), CH20 ($p = 0.005$) and emotional task with neutral emotions in CH4 ($p = 0.048$), CH5 ($p = 0.005$), CH11 ($p = 0.032$), CH13 ($p = 0.016$), CH14 ($p = 0.014$), CH15 ($p = 0.005$), CH16 ($p = 0.013$), CH17 ($p = 0.005$), CH18 ($p = 0.004$), CH19 ($p = 0.017$), CH20 ($p = 0.005$), respectively. There was no significant difference in brain activation between positive and neutral emotions. All significant channels were after controlling for the false discovery rate (FDR) [20]. In addiditon, neither behavioral data and brain activation in children did not differ by gender.

The correlation result showed that the reaction time of negative emotion condition was significantly associated with the reaction times of switch condition in the cognitive control task ($r = 0.583$, $p < 0.001$). The accuracy of the cognitive task was negatively correlated to the brain activation of negative emotion processing in CH17 ($r = -0.358$, $p = 0.032$). Furthermore, the reaction time and accuracy ($r = -0.578$, $p < 0.001$) of the cognitive control task were negatively correlated.

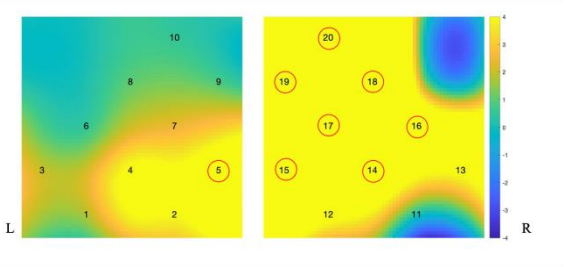

Figure 2. The main effect of brain activation among three emotions . Channels with significant differences in brain activation after controlling for FDR are shown in the yellow area with the red circle.

IV. Discussion

The present study sought to investigate the neural bases of negative emotion processing in early childhood and whether there is a correlation between children's negative emotion processing and cognitive ability. Our results demonstrated that the negative emotion condition had longer reaction times than the positive emotion condition and the negative emotion condition evoked greater brain activation than neutral and positive emotion conditions, suggesting affective emotion processing requires more brain activity than neutral emotion. The region was observed in bilateral DLPFC and MFG and the right IFG. Previous fNIRS studies have reported significantly increased HbO in bilateral ventrolateral PFC [21] and medial PFC and the upper left frontal gyrus when responding to negative images compared with neutral images [22]. An fMRI study in adolescents and adults showed significantly higher activation in frontoparietal regions when fearful faces were presented compared with neutral faces [23]. Our finding provides further evidence that in early childhood, negative emotion processing demands more neural resources than neutral and positive emotion processing.

We also found that negative emotion processing was negatively associated with the cognitive ability in children, where children who show higher accuracy in the cognitive control task revealed a lower brain activation in processing negative emotion. Previous research on cognitive control in children offered a basis for our finding that lower HbO is associated with higher accuracy and slower response times [15]. Thus, the present study indicated that children who show better performance in the cognitive control tasks spend a short time processing negative emotions. This is in line with previous research negative emotions trigger more brain activation compared with positive and neutral emotions and further demonstrates that children allocate more attention and cognition to deal with the negative emotion task [10,11]. In

turn, this suggesting children with better cognitive ability would spend less time processing negative emotions.

The behavioral and imaging results showed longer reaction times and higher activation in negative affective processing, respectively, compared to neutral and positive emotion processing. The association between the combined emotional attentional task and cognitive control task suggests that negative emotion processing requires greater demands on cognition compared with neutral and positive emotion processing during the combined emotional attentional task, which requires the integration of facial expression recognition, attention, and executive function. The executive function could help children to quickly adapt their thoughts and behaviors to cope with the requirements and goals of the task and effectively integrate information to respond [15]. The processing of emotions and cognition observed in our study may be explained by the shared processing resources model [24]. According to the model, negative emotions share processing resources with cognition so that an individual can implicitly modulate their emotional response to a negative stimulus. Therefore, the task of processing negative emotion produces longer reaction times and greater brain activation.

This study has several notable strengths. First, we developed a social-emotional task that allowed participants to interact with a partner. Second, we acquired fNIRS data to investigate the neural mechanisms underlying negative emotion processing, which offered biological evidence of emotion processing. Third, we studied young children to explore early emotional and cognitive development, which offers a basis for subsequent studies on emotion processing in non-typically developing children. There are also several limitations to our work. First, we only included a relatively small sample of typically developing children. For future work, we plan to study a larger sample of different ages to enable groupings by traits. Second, the emotional paradigm can be improved to provide a naturalistic task, so that the interactions between children and adults/peers better simulate emotions encountered in everyday life. Third, because of the inherent limitations of fNIRS, cerebral activity was only measured up to a maximum of 3 cm below the scalp, so we could not examine the activation of deeper structures.

In conclusion, the current study found that negative emotion processing in early childhood requires greater demands on cognition than neutral and positive emotion processing, and negative emotion processing was associated with cognitive ability. The initial years of life are a period of rapid emotional and cognitive development, our findings provide novel insight into the neural basis of negative emotion processing in children and offer understanding toward the precursors of psychopathology that may impair negative emotion processing during childhood.

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