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Differences in frontal EEG asymmetry during emotion regulation between high and low mindfulness adolescents

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ABSTRACT

The present study examined the differences in frontal EEG asymmetry during emotion regulation between participants who had different levels of trait mindfulness. EEG recordings were taken from 23 high mindfulness adolescents (M_{age} = 12.34) and 22 low mindfulness adolescents (M_{age} = 12.53) during the Reactivity and Regulation-Image Task. The results showed that (1) high mindfulness adolescents had greater left (relative to right) asymmetry than low mindfulness adolescents in down-regulation and up-regulation conditions; however, there was no significant difference in the non-regulation condition; (2) In the up-regulating condition, adolescents showed greater right (relative to left) asymmetry for negative stimuli compared to neutral stimuli; however, there was no significant difference in down-regulation and non-regulation conditions. The results provide neurological evidence that trait mindfulness was highly related to the regulation of emotions and affects how emotions are processed.

1. Introduction

Mindfulness affects emotion regulation practices such as decreased negative emotions (Goldin & Gross, 2010) and improvement in physical and mental health (Erisman & Roemer, 2010; Tan & Martin, 2015), etc. As a biomarker of emotion regulation and mindfulness, the electroencephalogram (EEG) asymmetry indicated that the frontal region played an important and essential role (Atzaba-Poria, Deater-Deckard, & Bell, 2017). Previous findings suggest that higher levels of trait mindfulness are associated with a higher quality of life, lower levels of physical pain, and negative affect in adolescents (Petter, Chambers, McGrath, & Dick, 2013). An understanding of the relationship between mindfulness and the frontal EEG asymmetry during emotion regulation in this important period might improve our understanding of socio-emotional development and create a possible assessment marker for the influence of mindfulness on emotion regulation in adolescence. Thus, the current study aimed to understand socio-emotional development, and create a possible assessment marker for mindfulness and emotion regulation for adolescents.

1.1. Mindfulness and emotion regulation

Mindfulness is defined as the awareness derived from focusing intentionally and nonjudgmentally on an experience in the present moment (Kabat-Zinn, 2003). The construct of trait mindfulness is conceptualized as a multifaceted, dispositional trait that is stable within a person unless cultivated through regular practice (Eisenlohr-Moul, Walsh, Charnigo, Lynam, & Baer, 2012). Trait mindfulness is composed of characteristics that involve different qualities of attention and self-regulation, with an emphasis on a non-judgmental, non-discursive awareness of one's perceptions, sensations, thoughts, and emotions (Deng, Gao, Zhang, & Li, 2020). There is much evidence backing the benefits of mindfulness practices for disorders such as hyperactivity (Schoenberg et al., 2014), and social anxiety (Goldin & Gross, 2010). Further, mindfulness improves mental health through adaptive responses during emotion regulation (Erisman & Roemer, 2010). Mindfulness is strongly correlated with emotion regulation because it involves a nonreactive awareness and acceptance of experiences at that moment (Galla, Kaiser-Greenland, & Black, 2016). Mindfulness has been shown to facilitate attentional processes and cognitive control during emotion regulation (Kaunhoven & Dorjee, 2017; Schoenberg, 2016). It allows individuals to improve self-regulatory processes by encouraging

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an effortlessly sustained attention in the present moment while disengaging from distractions (Pavlov et al., 2014). Mindfulness promotes moment-to-moment experiences and helps with cognitive control during emotion regulation (De Bruin, Zijlstra, & Bogels, 2014; Kallapiran, Koo, Kirubakaran, & Hancock, 2015). An improvement in cognitive control was observed in experienced meditators (Reva, Pavlov, Loktev, Korenyok, & Aftanas, 2014). Regular mindfulness practice decreases cognitive distortions by increasing mindful attitudes and dispelling anxious feelings (Goldin et al., 2016; Goldin, Morrison, Jazaieri, Heimberg, & Gross, 2017). Mindfulness shapes metacognitive awareness such that emotions are regarded as a changing state rather than a fixed trait, which might enhance the cognitive appraisal of subjective experiences.

People differ in the intensity and quality of their emotional response to stimuli. Emotional reactivity and regulation are two indicators that reflect the processes of emotion generation and emotion regulation (Silvers et al., 2012). Emotional reactivity indicates the intensity and degree of people's response to emotional stimuli. It also refers to the features of people's emotional responding, such as the threshold of stimuli needed to generate emotional responses (Carthy, Horesh, Apter, Edge, & Gross, 2010). Emotion regulation indicates the modification and control of one's emotional response (Deng, Sang, Ku, & Sai, 2019), and refers to an individual's attempt to change the emotional state they are experiencing. As two important indicators of the process of emotion generation and emotion regulation, trait mindfulness is strongly related to the reduction of emotional reactivity and the improvement of response regulation (Deng et al., 2020). Higher levels of trait mindfulness are associated with less reactivity to negative emotional stimuli. The impacts of mindfulness could counteract the reflexive emotional reactivity of emotions and reduce the activations of emotional stimuli during emotion regulation (Ho, Sun, K. H., Chan, & Lee, 2015). Higher levels of trait mindfulness are also highly related to stronger affect regulatory efficiency, greater self-awareness, understanding and acceptance of emotions, and a greater ability to modulate negative experiences (Edwards, Adams, Waldo, Hadfield, & Biegel, 2014). As such, many findings suggest the importance of investigating close relationships, mindfulness, and emotion reactivity and regulation.

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1.2. *Frontal EEG asymmetry during emotion regulation*

Recent research developments suggest that EEG can be a tool to link mindfulness and emotion regulation. Much evidence has demonstrated the relationship between emotion-related constructs and asymmetries in the electroencephalographic activity in the frontal cortex (Davidson et al., 2003). Frontal asymmetry in the alpha frequency band (8−13 Hz) is considered to be an important index of the functional association between the frontal lobe and the amygdala, the brain network for the processing of emotionally salient and relevant information (Atzaba-Poria et al., 2017). Left asymmetric activation suggests that the alpha power decreased from the left to the right hemisphere, while right asymmetric activation suggests that the alpha power decreased from the right to the left hemisphere (Wang, Lu, Gu, & Hu, 2018). Asymmetry score is commonly used as the index of frontal asymmetry (Papousek, Harald Freudenthaler, & Schulter, 2011). It is calculated as the subtraction between the natural log (ln) of the average alpha power values at left and right recording sites (e.g., Ln F4-Ln F3). Since the alpha power is inversely related to regional brain activity (e.g., Cook, O'Hara, Uijtdehaage, Mandelkern, & Leuchter, 1998), positive asymmetry scores indicate a relatively greater left hemisphere cortical activity (lower alpha power in the left than in the right hemisphere).

The different activation patterns of the frontal areas during the resting state and the aroused state could be reliable predictors of individual emotional reactivity and emotion regulation (Hannesdóttir, Doxie, Bell, Ollendick, & Wolfe, 2010). State and trait frontal EEG asymmetry scores were considered as indices of frontal influence on emotions (Goodman, Rietschel, Lo, Costanzo, & Hatfield, 2013). Frontal EEG asymmetry reflected both individuals' emotional reactivity and regulation of emotional responses.

As a predictor of emotional reactivity, frontal EEG asymmetry not only reflects the resting levels of activity but also the state-related activation, which indicates stable individual differences in both trait predispositions to the responses to emotional stimuli and changes in emotional states (Coan & Allen, 2004). Left and right frontal lobes differentially specialize in approach versus withdrawal tendencies, influencing the way people regulate when emotionally aroused (Jackson et al., 2003). For example, left prefrontal cortex activation has been observed during approach-oriented behavior and reactivity of positive emotions. Increased activation in the right prefrontal cortices has been observed during avoidance-oriented behavior and reactivity of negative emotions (Dennis & Solomon, 2010). Previous research revealed a significant correlation between frontal alpha asymmetry scores and the scores of behavioral activation system (BAS), indicating that higher BAS activity was associated with larger relative left hemisphere activity (Keune, Bostanov, Kotchoubey, & Hautzinger, 2012).

As a predictor of the regulation process, frontal EEG activity may not only reflect the degree to which an individual reacts to specific stimuli, but the degree to which they are capable of responding to the emotional demands in a specific situation (Coan, Allen, & McKnight, 2006). For instance, effective emotion regulation is related to greater relative left frontal activity, as measured by frontal alpha asymmetry (Choi, Sekiya, Minote, & Watanuki, 2016). It may more accurately be thought of as a predictor of emotion regulatory abilities (Papousek et al., 2011). For example, frontal EEG asymmetry could be a possible explanation of the individual difference that is relevant to affective disorder or emotional dysfunction (Coan & Allen, 2004). Moreover, other research found that emotion regulation indexed by the frontal EEG asymmetry contributed to the prediction of resilient functioning among high-risk children (Curtis & Cicchetti, 2007). Nonresilient children showed larger right hemisphere activity, indicating that a withdrawal emotional style is related to those children manifesting extreme levels of maladaptive functioning. Another study documented that participants with greater left relative to right activation in anterior scalp-recoding sites displayed a greater magnitude of negative emotion regulation (Jackson et al., 2003). Compared with passive viewing, relative left frontal activity was greater when participants were instructed to use reappraisal strategy, which was highly related to positive affectivity and better psychological wellbeing (Choi et al., 2016; Wang et al., 2018). The frontal EEG asymmetry is also considered to be a reliable indicator of an individual difference related to psychopathology or risk for psychopathology (Coan & Allen, 2004). For example, relative right-sided frontal EEG asymmetry was strongly associated with both depressive and anxious symptomatology (Allen & Reznik, 2015; Grünewald et al., 2018; Nusslock, Walden, & Harmon-Jones, 2015). A longitudinal EEG study found that relatively larger right parietal asymmetry is related to increased negative emotional experiences (e.g., fear and anxiety) and poorer emotion regulation during development (Hannesdóttir et al., 2010). A previous study showed that participants with larger frontal asymmetry scores (larger alpha power of right hemisphere) would have less difficulty with everyday emotion regulation, especially with impulse control (Zhang, Hua, Xiu, Oei, & Hu, 2020). Altogether, prior findings from the EEG asymmetry documented the role of left frontal activity in promoting emotion regulatory behaviors.

1.3. Mindfulness of adolescents

Taken together, there is no question that it is important to understand the role of mindfulness in emotion regulation in order to make advances in our knowledge of human cognition and behavior. There have been quite a few studies with adult samples with promising results in the past; an EEG study examined the influence of 8 weeks of mindfulness training on frontal EEG asymmetry. Results showed that frontal EEG asymmetry scores at 8 weeks were significantly higher than frontal EEG asymmetry scores at baseline and at 4 weeks during emotional challenges, providing neural evidence of the positive impacts of mindfulness in emotion regulation (Zhou & Liu, 2017). Other research found that guided mindfulness meditation increased relative left frontal asymmetry, indicating a neural pattern of increased approach motivation of high-risk depressed patients (Keune, Bostanov, Hautzinger, & Kotchoubey, 2013; for contrary results, see also: (Keune, Bostanov, Hautzinger, & Kotchoubey, 2011; Szumska, Gola, & Rusanowska, 2020).

However, mindfulness in adolescents has not been examined much yet. Adolescence is a period of profound changes in metacognitive functions. A universal process of spiritual "awakening" and an increasing inner awareness are reported amongst adolescents (Cobb, Kor, & Miller, 2015). Such increased observation of inner experiences is one of the core components of trait mindfulness. In addition, as adolescents develop a more sophisticated awareness of internal experiences, a more complex set of differentiated mindfulness skills and multi-faceted trait mindfulness structure may develop compared to their younger counterparts (Pallozzi, Wertheim, Paxton, & Ong, 2017).

High levels of trait mindfulness necessitate significant executive functioning and self-control. Trait mindfulness reflects the operation of higher-order processes that facilitate emotion regulation (Lyvers, Makin, Toms, Thorberg, & Samios, 2014). A mature capacity to regulate one's thoughts, feelings, and behavior must be developed for an individual to be mindful. However, these abilities are still developing during adolescence (Ciesla, Reilly, Dickson, Emanuel, & Updegraff, 2012). A previous study indicated that adolescents who had higher levels of trait mindfulness would use significantly more reappraisal in their daily lives, which is considered to be a more adaptive regulatory strategy (Zhang et al., 2019). Moreover, emotion regulation is linked to activity within the prefrontal cortex, a brain region essential for normal executive cognitive function (Atzaba-Poria et al., 2017). This region is not completely developed until late adolescence. Therefore, adolescents understandably have lower levels of trait mindfulness (Royuela-Colomer & Calvete, 2016), which may indicate their immature executive functioning and self-control. In this sense, adolescents with higher levels of trait mindfulness appear more likely to have higher functional integrity of the prefrontal cortex, which is highly related to more-efficient frontal lobe executive functioning and self-control.

As an emotionally turbulent period, structural and functional neural changes occurring during adolescence may require a greater demand on emotion regulation (Deng, Sang, & Luan, 2013). Therefore, further research is needed to better understand the relationship between trait mindfulness and emotional regulation in adolescents. An improved understanding may also provide important theoretical and practical information to promote adolescents' mental health and improve the efficiency of emotional adjustment at this particular age.

1.4. The present study

Adolescence is an important period for socio-emotional development (Deng et al., 2013). Stephanou et al. (2016) observed higher emotional reactivity in adolescents, and this emotional reactivity decreases with age. On the other hand, adolescents show a lower level of successful emotion regulation because of their relatively immature prefrontal function. Adolescents are generally only flexible and efficient in emotion regulation after complete cognitive control capacity develops (Griffith, Dubow, & Ippolito, 2000). Electrophysiological evidence reveals structural and functional changes in several brain regions during adolescence. The cortical region is more emotionally reactive in adolescents (Burnett & Blakemore, 2009) and shows more activation during emotion regulation (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Based on these findings, adolescents have a greater regulatory demand. Thus, the current study is particularly important and unique contribution to the field.

Many empirical studies have suggested that mindfulness improves attentional orientation, inhibitory control, and cognitive flexibility (e.g., Napoli, Krech, & Holley, 2005; Felver, Frank, & McEachern, 2014). As a biomarker of effective emotion regulation, frontal EEG asymmetry reflects the balance of brain activation in the left and right frontal areas. Although researchers have attempted to explore the relationship between trait mindfulness and emotion regulation, little evidence is available that describes how trait mindfulness affects brain activation when adolescents regulate their emotions. As a biomarker of emotional reactivity and effective regulation, frontal EEG asymmetry reflects the balance of brain activation in the left and right frontal areas (Papousek et al., 2011). In the present study, we examined the frontal EEG asymmetry during emotion regulation between participants who had different levels of trait mindfulness.

Differences in frontal EEG asymmetry could explain significant variance in emotion regulation (Goodman et al., 2013). A previous study showed that larger right frontal activity indicated that people might be more sensitive and have faster withdrawal responses to negative emotions. Larger left frontal activity indicated people might have a high level of impulse control, which might be a possible cause of effective regulation (Zhang et al., 2020). Therefore, we hypothesized that adolescents with higher levels of trait mindfulness would have greater left (relative to right) asymmetry than low mindfulness adolescents when up- or down-regulating emotional stimulus rather than a passive view. Moreover, an ERP study indicated that the effects of mindfulness during emotion regulation and emotional processing were reflected by reducing emotional stimulus, especially for negative emotional stimulus (Deng, Zhang, Hu, & Zeng, 2019, 2020; Ho et al., 2015). Therefore, we predicted that adolescents with higher levels of trait mindfulness would have greater left (relative to right) asymmetry than low mindfulness adolescents when regulating negative emotional stimuli.

2. Methods

2.1. Participants

Participants were recruited on the basis of their scores on the Five Facet Mindfulness Questionnaires (FFMQ, Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006). The 39-item FFMQ is used to assess adolescents' trait mindfulness level on a 5-point Likert scale (1= never or very rarely true, 5= very often or always true; e.g., "I intentionally stay aware of my feelings"). We averaged across the 39 items (after reverse scoring the relevant items) to create the total score of the adolescents' trait mindfulness level (α = .821).

The scale was administered initially in a large sample (***N*** = 92; 49 females and 43 males). Responders in the top 27 % of the distribution were assigned to high trait mindfulness group whereas those in the bottom 27 % to low trait mindfulness group. Given the poor EEG data quality and technical error, 3 participants were excluded from the study. Thus, the final sample was composed of 22 low mindfulness adolescents (LMS; 11 male and 11 female, aged from 11 to 15 years old, *M*age = 12.53, *SD* = 1.10) and 23 high mindfulness adolescents (HMS; 9 male, and 14 female, aged from 10 to 14 years, M_{age} = 12.34, *SD* = .88). HMSs (M_{HMSs} = 129.39, SD = 5.84) and LMSs (M_{LMSs} = 107.36, *SD* = 4.50) differed significantly on the overall trait mindfulness score ($p < .001$). The sample size in this study was also in line with typical ERP studies (Dennis & Hajcak, 2009; Langeslag & Van Strien, 2010).

Adolescent participants were recruited via flyers that invited healthy volunteers to participate in a study of mental health and emotion. All of the adolescents came from urban communities in Shenzhen city in China. In the sample, 33.33 % of the adolescents were only children, whereas the others had one or more siblings. Approximately 51.11 % of fathers and 46.67 % of mothers had received a college education, whereas other parents had received an education of high school or lower. All of the participants were right-handed and had a normal or corrected-to-normal vision, and were in good neurological and psychiatric condition. No participant had a history of neurological or psychiatric disorder, as determined by self- and/or parent report. The research protocol was approved by the local Institutional Review Board. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the participants and their parents before the study, and the participants were fully debriefed after the experiment.

2.2. Stimuli

Eighty pictures were selected from the Chinese Affective Picture System (CAPS; Bai, Ma, Huang, & Luo, 2005); 40 negative (valence: M = 2.35, SD = .21; arousal: M = 5.59, SD = .29) and 40 neutral (valence: M = 5.39, SD = .70; arousal: M = 3.63, SD = .84). Results of the t-tests showed that negative and neutral pictures significantly differed in terms of valence and arousal ratings. The negative pictures were more arousing and less pleasant than the neutral pictures (both p values < .001). The pictures were age-appropriate for adolescents. The negative picture set included unpleasing social situations and frightening animals, and the neutral pictures depicted subjects such as household objects. The pictures (330 × 340 pixels) were presented in color by a 19-in monitor that occupies approximately 35° of the visual angle horizontally and vertically.

2.3. Procedures

We employed a 2 (Group: HMSs vs. LMSs) × 2 (Valence: negative vs. neutral) × 3 (Strategy: non-regulation vs. up-regulation vs. down-regulation) repeated measures design. After receiving the demographic information from the participants, the Reactivity and Regulation-Image Task (REAR-I) began. The REAR-I task has been shown to successfully assess both emotional reactivity and emotion regulation in an adolescent sample in prior research (Deng, Zhang et al., 2019). Before the experiment, the participants were introduced to the procedures of the REAR-I task by using the instructions adapted from Ochsner et al.'s (2004) and Moser, Krompinger, Dietz, and Simons's (2009) studies. They were told that they would need to regulate their emotions according to three possible cues (up-regulating emotions, down-regulating emotions, and non-regulation). For the up-regulation conditions, the participants were instructed to view the picture from a first-person perspective as someone personally participating in the pictured event. For the down-regulation conditions, the participants were instructed to view the picture either from a third-person perspective as someone with no personal relevance to the pictured event/object or as if the image were fake. For non-regulation conditions, the participants were asked to passively view the pictures and respond naturally.

Before the formal experiment started, a primary manipulation check was conducted to determine whether the participants understood the instructions. The research assistant asked the participants how they responded to the task in different experimental conditions. Responses from the participants indicated that they all understood the instructions and could regulate their emotions according to the instructions.

First, the instruction of emotional regulatory strategies (up-regulation, down-regulation, or non-regulation) was shown on the screen for one second. One negative or neutral picture was then shown for three seconds. The participants were told to passively watch the picture or to regulate their emotion to the picture by using the instructed strategy. Then, the participants were asked to rate their current intensity of emotion on a 7-point scale (i.e., How strongly do you feel after viewing the picture? 1 = very weak emotion, 7 = very strong emotion) by pressing a button. Last, there was an intertrial interval for 1.5 s.

There were 4 runs in the task. Each run consisted of 6 experimental blocks. There were 10 trials in one experimental block. Only one experimental condition was presented in one block. The 6 experimental blocks were randomly shuffled within one run. There were 60 trials in each run with 240 experimental trials in the overall task. Each picture was repeated three times for each of the three regulatory instructions. The task was administrated by using E-Prime software. An experimental session took 30−35 min for each participant (see Fig. 1).

2.4. Psychophysiological recording, data reduction, and analysis

EEG activity was recorded continuously via a 64 passive scalp electrode amplifier BrainAmp, Brain Products, Germany) based on the 10/10 system, with two electrodes placed on the left and right mastoids. The EEG was sampled at 500 Hz and impedance was kept below 5kΩ. The data were re-referenced offline to the averaged mastoid references, and the bandpass was filtered from 1 Hz to 30 Hz (Yadon & Daugherty, 2018). Eye movements and blink artifacts were corrected by using the independent component analysis (ICA) algorithm implemented in Brain Vision Analyzer 2.0 ("Brain Products", Germany). The artifact scored epochs were eliminated from all subsequent analyses.

EEG data from all 3 s presentation of the picture was taken into analysis. All artifact-free EEG data were transformed into raw power scores using a Fast Fourier Transformation (FFT), with a Hanning window of 1-s width and 50 % overlap by using the Brain Vision Analyzer 2.0. Power spectra (epoch length 1-s) were averaged across all artifact-free intervals for both mindfulness groups. Power values were averaged across 1-s segments across different experimental trials. Asymmetry within the alpha frequency band (8−13 Hz) was used for the analyses. According to the existing literature (Dennis & Solomon, 2010; Papousek et al., 2011), the dorsolateral frontal positions F3 and F4 were used for the analyses. Average alpha power values at F3 and F4 were log-transformed using the natural log (ln). EEG power data were transformed using the natural log to normalize the distribution. EEG data for

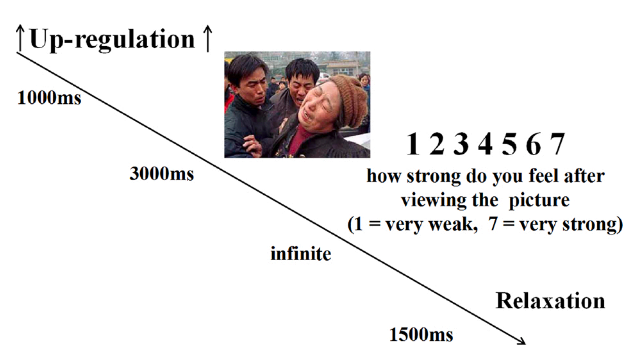

Fig. 1. Sample stimuli and procedure.

each group and condition were examined via histograms for normality. Moreover, Kolmogorov-Smirnov tests were run between groups for each condition to test for normality. Based on the results of the Kolmogorov-Smirnov tests, the assumption of normality was not violated (Kolmogorov-Smirnov Z = .45~.68; p = .75~.99). Asymmetry scores were calculated as follows: Ln F4-Ln F3. Alpha power is inversely related to regional brain activity (e.g., Cook et al., 1998). Consequently, positive asymmetry scores indicate a relatively greater left hemisphere cortical activity (lower alpha power in the left than in the right hemisphere).

Using the natural log-transformed EEG power in the alpha bandwidth from frontal recording sites during different regulatory conditions, we examined the impact of the emotion regulation on EEG asymmetry in groups of adolescents with different levels of trait mindfulness. Asymmetry scores in the different experimental conditions were examined by using a 2 (Group: HMSs vs. LMSs) X 2 (Valence: neutral vs. negative) X 3 (Strategy: up-regulation vs. non-regulation vs. down-regulation) repeated measures ANOVA. The asymmetry scores were statistically evaluated using SPSS 20.0. The significance level was set at $p < 0.05$, and Greenhouse-Geisser correction was applied to p values associated with multiple-df comparisons. Partial eta squared was reported as a measure of effect size.

3. Results

Prior to the repeated measures ANOVA, Levene's tests were run between different mindfulness groups for each condition to test the assumption of homogeneity of variance between different mindfulness groups. Based on Levene's tests of homogeneity of variance, the assumption of homogeneity of variance was not violated (F = .28~2.81; p = .10~.87). Table 1 showed the group differences between the six regulation conditions.

The main effect of Group was significant, $F(1,43) = 6.11$, $p = .018$, $\eta_p^2 = .12$. LMSs had significantly smaller asymmetry scores compared to HMSs. The main effect of Valence was not significant, $F(1,44) = 1.92$, $p = .173$, $\eta_p^2 = .04$. The main effect of Regulation Strategy was not significant, $F(2,86) = .01$, $p = .992$, $\eta_p^2 = .00$.

The interaction of Group and Regulation Strategy was significant, $F(2,86) = 3.47$, $p = .035$, $\eta_p^2 = .08$. Post-hoc tests showed that the asymmetry scores of HMSs were significantly larger than those of LMSs when they used up-regulation, $p = .005$ and down-regulation strategy, $p = .015$. However, there was no significant difference in the asymmetry scores between LMSs and HMSs in non-regulation conditions, $p = .218$. See Fig. 2.

The interaction of Valence and Regulation Strategy was significant, $F(2,86) = 3.53$, $p = .034$, $\eta_p^2 = .08$. Post-hoc tests showed that the asymmetry scores of negative up-regulation conditions were significantly smaller than those of neutral up-regulation conditions, $p = .013$. However, there were not significant differences in other strategies (down-regulation: $p = .576$; non-regulation: $p = .632$).

The interaction of Group and Valence was not significant, $F(1,43) = .43$, $p = .515$, $\eta_p^2 = .01$. The three-way interaction of Group × Valence × Regulation Strategy was not significant, $F(2,86) = .90$, $p = .411$, $\eta_p^2 = .02$.

Table 1
The asymmetry scores under different conditions between LMSs and HMSs.

Asymmetry Scores	LMSs	HMSs	*t*	*d*	95 %*CI*	*p*
Negative emotion up-regulation	−0.005	0.077	−2.742	−0.838	[-.142, -.022]	0.009
Negative emotion down-regulation	0.016	0.115	−2.685	−0.823	[-.174, -.025]	0.010
Negative emotion non-regulation	0.037	0.078	−1.299	−0.396	[-.105, .023]	0.201
Neutral emotion up-regulation	0.038	0.134	−2.334	−0.712	[-.178, -.013]	0.024
Neutral emotion down-regulation	0.03	0.081	−1.607	−0.49	[-.116, .013]	0.115
Neutral emotion non-regulation	0.05	0.08	−0.897	−0.298	[-.097, .037]	0.374

Note. HMS = high mindfulness adolescent; LMS = low mindfulness adolescent.

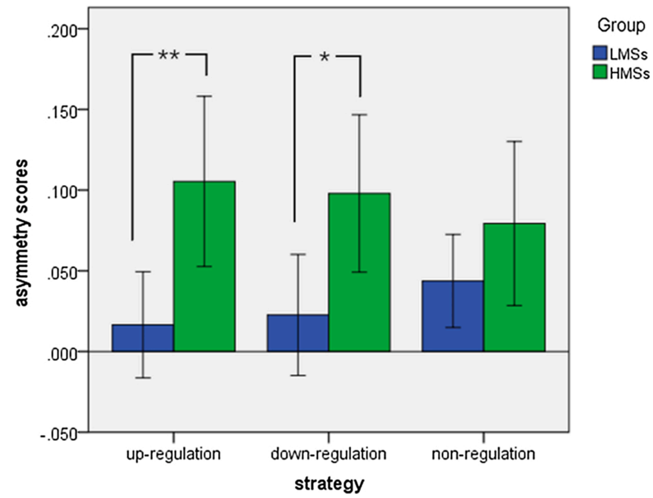

Fig. 2. The asymmetry scores under different conditions between LMSs and HMSs.
Note. HMS = high mindfulness adolescent; LMS = low mindfulness adolescent. Error Bars represented +/- 1 standard error (SE).

4. Discussion

Trait mindfulness has been characterized as self-awareness derived from intentionally and nonjudgmentally paying attention to experiences in the present moment (Burzler, Voracek, Hos, & Tran, 2018). Previous studies have described the impact of mindfulness on emotion regulation (Felver et al., 2014; Napoli et al., 2005). However, to our knowledge, little neuroscientific evidence has described how trait mindfulness is related to frontal brain activations during emotion regulation at this particular age. The present study aimed to examine the differences in the frontal EEG asymmetry during emotion regulation between adolescents with different trait mindfulness levels and to provide psychophysiological evidence for this relationship. By identifying the relationship between trait mindfulness and the frontal EEG asymmetry emotion regulation, we have the ability to identify the neural underpinnings of mindfulness that influence human behaviors.

In adolescence, a universal process of "mental awakening" may increase the level of mindfulness (Cobb et al., 2015). The results of the present study were consistent with the hypothesis that trait mindfulness is related to frontal electrocortical activity during the regulation of negative and neutral emotions (Felver et al., 2014; Lyvers et al., 2014; Napoli et al., 2005). High mindfulness adolescents had greater left (relative to right) asymmetry than low mindfulness adolescents during emotion regulation. Specifically, in down-regulation and non-regulation conditions, high mindfulness adolescents had greater left (relative to right) asymmetry than low mindfulness adolescents. Previous research has found that high trait mindfulness was associated with adaptive emotion regulation, which may lead to an increased function in frontal regions (Davidson et al., 2003). Also, mindfulness training led to greater left (relative to right) asymmetry during emotional challenge by increasing the activation of frontal regions regarding emotional control and executive function (Zhou & Liu, 2017). The current study expands previous studies by showing that a higher level of mindfulness might not only promote the early recognition of emotional stimuli (Galla et al.,

2016) but also be highly related to an increased function in frontal regions (e.g., high level of cognitive control and better regulatory efficiency).

Since adolescents experience increasing hormonal changes and developmental challenges, they are relatively highly emotionally reactive and turbulent in this special age period (Blakemore, 2012). The high emotionality and emotional turbulence of adolescents render them vulnerable to emotion-related problems. A higher level of mindfulness may temper the negative impacts of dysregulation. Based on the results of the present study, mindfulness might function to directly increase the active recruitment of “affective regulation” brain regions (the left prefrontal cortex). This finding is also consistent with the findings from behavioral studies showing that the increase in self-awareness induced by mindfulness improves inhibitory control and cognitive flexibility during emotion regulation (Felver et al., 2014). Especially for those adolescents whose “higher” brain regions are still developing, the cultivation of mindfulness skills may help them regulate their emotions effectively.

Frontal EEG asymmetry not only reflects the level of activity in the resting state but also reflects the state-related activation, which measures the stable differences between individuals’ responses to emotional stimuli and changes in emotional states (Coan & Allen, 2004). In the current study, we only found low and high mindfulness group differences in the frontal EEG asymmetry when adolescents used specific regulatory strategies (in the up- and down-regulation conditions), but not during baseline (in the non-regulation conditions). In this case, mindfulness might have a greater benefit on emotion regulation in increasing the prefrontal functions during changes in the emotional responses rather than providing a better resting emotional state before regulation. This is consistent with the previous results that frontal EEG activity measured during emotion regulation is a better predictor of emotion regulatory capability in specific emotional contexts compared to EEG measured during baseline (Dennis, 2010). This also provides a complementary perspective on the well-documented statement that mindfulness promotes emotion regulation mainly by reducing the negative reactivity to emotional stimuli during early emotional processing (Deng, Sang et al., 2019).

The results of the current study also indicated that adolescents showed greater left frontal asymmetry in neutral up-regulation conditions than those in negative up-regulation. A previous study suggested that greater relative left frontal activity was related to decreased response to negative stimuli and increased positive emotions because of approach motivations during emotion regulation (Choi et al., 2016; Keune et al., 2013). Individuals with decreased relative left frontal asymmetry are prone to experience a decrease in approach motivation (Nusslock et al., 2015). In the present study, all the picture stimuli were selected from the Chinese Affective Picture System (CAPS; Bai et al., 2005). The neutral stimuli were more pleasant than the negative emotional stimuli (valence of the stimuli: $M_{negative} = 2.35$, $M_{neutral} = 5.39$). Therefore, compared with the up-regulation of negative emotional stimuli, the up-regulation of neutral stimuli better reflected the approach motivations of the participants which were indexed by the greater left frontal asymmetry. This interpretation is in line with previous studies of frontal EEG asymmetry as a neutral pattern indicative of approach-related motivations.

Partial eta square used to indicate a measure of the proportion of variance accounted for by a predictor. Partial eta squares between .01 and .06 indicated a small effect size. Partial eta squares between .06 and .13 indicated a medium effect. Partial eta squares greater than .13 indicated a large effect (Cohen, 1988). In the current study, partial eta squares were ranged from 0.01 to .12. For the most important results, the partial eta squares were .08, .08, and 0.12 respectively. In the literature for youth and adults (references listed in the current study), partial eta squares were reported ranged from 0.05 to .12. Effect sizes obtained in the current study indicated a medium effect and replicated effect sizes for EEG asymmetry-regulation and EEG asymmetry-mindfulness links reported in the literature for youth and adults (Curtis & Cicchetti, 2007; Dennis & Solomon, 2010; Papousek et al., 2011).

Such findings deepen our understanding of the relationship between emotion regulation and mindfulness in a special period during human development. Particularly it implicates that having high mindfulness may make overcoming emotional obstacle less difficult compared to low mindfulness, especially in adolescence. Also, encouraging cultivation of trait mindfulness may enhance adolescents’ emotion regulation, which could benefit their emotional lives. In this case, cultivating trait mindfulness during adolescence may have value for school programs, especially for adolescents who are at risk of affective problems. Mindfulness related programs could facilitate a smooth transfer from the “storm and stress” stage to the post-adolescence period. Also, as a reliable index of effective regulation, the diagnostic values of frontal EEG asymmetry were again verified in the current study.

4.1. Limitations and future directions

The present study examined the relationship between trait mindfulness and frontal EEG asymmetry during emotion regulation in adolescents. Because of the nuances of negative emotions and the evolutionary approaches to human emotion, we only focused on negative emotion regulation (Goldin, McRae, Ramel, & Gross, 2008; Mauss, Cook, & Gross, 2007). It is important and necessary for future research to explore positive emotion regulation. Furthermore, in order to examine the developmental trajectory of mindfulness and its relation to brain development and maturity, we could use longitudinal design as a potential approach to employ in future research.

Limitations notwithstanding, the findings of the current study contribute to the literature on the influence of mindfulness on emotion regulation in adolescence. The current findings indicate that the impacts of mindfulness during emotion regulation could be related to significantly increased left-sided activations in the prefrontal regions as indicated by greater EEG asymmetry. As an important indicator of effective regulation and psychopathology, greater EEG asymmetry in high mindfulness adolescents also suggested that trait mindfulness might reduce adolescents’ vulnerability to psychopathology risks and improve the effectiveness of emotion regulation. Last but not least, the present study warrants further investigation of mindfulness in this special age.

Ethical approval

The research protocol was reviewed and approved by the Institutional Review Board of Shenzhen University. All procedures performed in studies involving human participants were conducted in accordance with the ethical standards of the Institutional Review Board of Shenzhen University and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A

Participants were asked to complete the Emotion Regulation Questionnaire (ERQ; Gross & John, 2003) and the PANAS-C scale (Laurent et al., 1999) before the study. The ERQ was selected to measure the habitual use of emotion-regulation strategies (e.g., reappraisal and suppression) as an index of trait emotion regulation styles. The PANAS-C was widely used to measure negative and positive emotional states of children and adolescents as an index of current levels of positive/-negative affect. T-tests showed that HMS and LMS groups didn't differ on the ERQ (reappraisal/ suppression) scores and the PANAS-C positive and negative affect scores (all t values < 1.62; p values > .131).

Regarding scores of ERQ and PANAS-C as covariates, repeated measures ANOVA were conducted to examine the relations between self-report data and EEG asymmetry results. Results of the repeated measures ANOVA indicated that all of the main effects of the self-report scale scores on the asymmetry scores (LnF4-LnF3) were not significant. Therefore, the self-report scale scores were not included in subsequent EEG analyses.

For ERQ : $F(1,42) = 1.649$, $p = .206$, $\eta_p^2 = .038$;
For PANAS-C positive subscale: $F(1,12) = .675$, $p = .429$, $\eta_p^2 = .058$;
For PANAS-C negative subscale: $F(1,12) = .035$ $p = .855$ $\eta_p^2 = .003$.

Appendix B

Participants rated their current emotional intensity after emotion regulation in the different experimental conditions. Participants' self-report ratings of their current emotional intensity in the different experimental conditions were examined by using a 2 (Group: HMSs vs. LMSs) × 2 (Valence: neutral vs. negative) × 3 (Strategy: up-regulation vs. non-regulation vs. down-regulation) repeated measures ANOVA.

Results showed that the main effect of valence was significant, $F(1,43) = 92.447$, $p<.001$, $\eta_p^2 = .683$. Participants had significantly higher self-report ratings of emotional intensity in the negative conditions than in the neutral conditions. The main effect of strategy was significant, $F(2,86) = 31.725$, $p<.001$, $\eta_p^2 = .425$. Participants' self-report ratings of emotional intensity in the up-regulation conditions were significantly higher than those in the non-regulation conditions. Participants' self-report ratings of emotional intensity in the non-regulation conditions were significantly higher than those in the down-regulation conditions. The main effect of group was not significant, $F(1,43) = .044$, $p = .834$, $\eta_p^2 = .001$.

The interaction of group and regulation strategy was not significant, $F(2,86) = 3.047$, $p = .053$, $\eta_p^2 = .066$. The interaction of valence and regulation strategy was significant, $F(2,86) = 5.931$, $p = .004$, $\eta_p^2 = .121$. In the negative stimulus conditions, self-report ratings of emotional intensity were larger in up-regulation than in non-regulation condition ($p = .001$). Self-report ratings of emotional intensity were larger in non-regulation than in down-regulation condition ($p < .001$). In the neutral valence condition, self-report ratings of emotional intensity were larger in up-regulation than in non-regulation condition ($p = .001$). Self-report ratings of emotional intensity were larger in non-regulation than in down-regulation condition ($p = .049$). The interaction of valence and group was not significant, $F(1,43) = 2.027$, $p = .162$, $\eta_p^2 = .045$. The three-way interaction of group × valence × regulation strategy was not significant, $F(2,86) = .263$, $p = .769$, $\eta_p^2 = .006$.

Correlation analyses were conducted between the EEG data and the self-report rating measures during the task in different conditions between groups. Results showed that there was no significant correlation between the EEG data and the self-report data (for HMSs: $r = 0.006 \sim .291$, $p = .169 \sim .997$; for LMSs: $r = 0.099 \sim .328$, $p = .136 \sim .661$).

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