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Event-related synchronization of delta and beta oscillations reflects developmental changes in the processing of affective pictures during adolescence

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ABSTRACT

Recent research has determined that affective pictures modulate event-related delta and beta oscillations in adults. However, it is unclear whether these brain oscillations reflect developmental changes in the processing of affective information during adolescence. EEG data were collected from 51 adolescents and 18 undergraduates as they viewed a total of 90 pictures. In the range of fast wave activities, event-related synchronization (ERS) in the beta band varied with emotional valence, indicating that beta ERS is indicative of early bottom-up processing of visual emotional stimuli. Adolescents at the age of 12 years exhibited more positive beta ERS amplitudes over posterior brain regions for positive versus neutral pictures compared to adolescents at the ages 14 years, 16 years and in young adults; however, no age-related differences were found for negative versus neutral pictures. In the range of slow wave activities, delta ERSs and late positive potential (LPP) amplitudes exhibited affective modulation and decreased over anterior brain regions from between the age of 12 years and early adulthood. These slow wave activities (delta and LPPs) reflected top-down attention to the motivational relevance of the emotional stimuli. Taken together, these observations suggest that adolescents exhibit dissociable ERS patterns in the delta and beta bands during affective processing. Furthermore, adolescents undergo age-dependent changes in oscillatory brain reorganization. Our results should be useful to researchers interested in affective processing during adolescence.

1. Introduction

Adolescence is a developmental period that is associated with increased vulnerability to stress, particularly with respect to affective stimuli (Dahl, 2004; Somerville et al., 2010; Spear, 2000). Behaviorally, adolescents display heightened responses to both positive and negative environmental stimuli compared with children and adults (Brenhouse and Andersena, 2011; Somerville et al., 2010). Neuroimaging research has shown that adolescents exhibit greater differences in responses in the amygdala in response to both fearful and happy facial expressions versus neutral facial expressions than do children and adults (Monk et al., 2003; Williams et al., 2006). However, these studies did not assess electrocortical changes in the processing of affective information. In this study, we used event-related potentials (ERPs) and event-related oscillations (EROs) to explore developmental changes in affective processing during adolescence.

Numerous ERP studies of affective processing have determined that the late positive potential (LPP) is a measure of emotional reactivity in adults. The LPP is a positive component with a central-parietal scalp distribution that begins within a few hundred milliseconds after stimulus onset and is sustained for seconds (Cuthbert et al., 2000; Weinberg et al., 2012). Positive and negative pictures elicit larger LPP amplitudes compared to neutral pictures (Foti and Hajcak, 2008; Hajcak and Nieuwenhuis, 2006; Hajcak et al., 2009; Schupp et al., 2004; Yen et al., 2010), indicating that the LPP reflects an increase in attention to visual emotional stimuli (Lang et al., 1997; Schupp et al., 2006). Moreover, the LPP shows age-dependent changes during childhood. For example, children aged 5–8 years and 8–13 years of age exhibit increased LPP activities while viewing emotional pictures relative to neutral pictures from the international affective picture system (IAPS) (Hajcak and Olvet, 2008; Kujawa et al., 2012).

Additionally, EROs are a powerful tool for the study of electrocortical changes in emotional processing including bottom-up and top-down processes (Aftanas et al., 2003a, 2003b; Knyazev, 2011). Bottom-up processing rapidly deploys attention to the properties of a sensory stimulus and results in fast wave activities (e.g., beta oscillations) (Baluch and Itti, 2011; Siegel et al., 2000). In contrast, top-down

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processing requires more effort to pay attention to behaviorally relevant events and results in slow wave activities (e.g., delta oscillations) (Mathes et al., 2006; Siegel et al., 2000). Delta oscillations (0.5–3.5 Hz) originate not only from subcortical areas, such as the nucleus accumbens (Leung and Yim, 1993), the ventral tegmental area (Grace, 1995), and the ventral pallidum (Lavin and Grace, 1996), but also from cortical regions, such as the medial prefrontal, anterior cingulate, and orbit frontal cortices (Dang-Vu et al., 2008). Moreover, cortical sources of delta activity show extensive reciprocal connectivity with various cortical, midbrain, and limbic structures (Alper et al., 2006) that are implicated in motivational brain circuits (Knyazev, 2012). Enhanced delta activity in the P300 paradigm is related to the motivational relevance of the task and the salience of the target stimulus (Knyazev, 2007). Additionally, IAPS pictures elicit synchronized delta power after stimulus onset (Klados et al., 2009). Increased delta power is observed in response to highly arousing, but not minimally arousing, IAPS pictures (Balconi et al., 2009). Delta synchronization intensifies upon the presentation of emotional stimuli during explicit and implicit emotional processing (Knyazev et al., 2009).

Within the range of fast wave activities, beta oscillations (15–30 Hz) have been proposed to represent a cortico-cortical process that indexes local information processing (Jensen et al., 2005) and are associated with emotional and cognitive processes (Ray and Cole, 1985). Several studies have revealed significant roles of early beta responses in face recognition and the differentiation of known and unknown faces (ÖzgÖren et al., 2005; Başar et al., 2006, 2007). A growing number of studies have shown that affective stimuli elicit event-related beta responses (Güntekin et al., 2010); however, previous studies have produced contradictory results. Some studies have stressed the negativity bias of beta responses toward negative stimuli. For example, a reliable early beta oscillation in the visual cortex rapidly discriminates aversive IAPS images (Keil et al., 2007). Negative pictures elicit greater beta response amplitudes in parietal and occipital electrodes when compared with neutral pictures (Güntekin et al., 2010). Beta responses to angry faces are greater amplitude compared to those elicited by happy faces (Güntekin and Başar, 2007). Other studies have suggested that both negative and positive images from the IAPS elicit greater beta synchronization than neutral images (Cohen et al., 2012; Hummel and Gerloff, 2006; Miskovic and Schmidt, 2010). Another study suggested that beta frequencies are not modulated by facial expressions (Balconi and Pozzoli, 2007). However, the exact functional significance of event-related beta oscillations in affective processing has yet to be determined.

To date, few studies have used event-related delta and beta oscillations to study affective information processing during adolescence. The adolescent brain undergoes structural and functional reorganization via through increased synaptic pruning and continued intra-cortical myelination (Brenhouse and Andersena, 2011; Thompson et al., 2000; Yurgelun-Todd, 2007). During adolescence, the normal pattern of EEG maturation involves a redistribution of relative EEG power as a function of age because posterior regions mature earlier than anterior regions (Segalowitz et al., 2010). Developmental reductions in the amplitudes of oscillations over a wide frequency range (e.g., delta and beta) continue until early adulthood (Uhlhaas and Singer, 2011). Moreover, developmental decreases in EEG power are accompanied by reductions in BOLD power and gray matter volume (Lüchinger et al., 2011, 2012; Whitford et al., 2007), all of which increase cortical efficiency later in development (Rypma, 2007). Thus, adolescents progressively improve their selective attention capacities for affective processing (Durston et al., 2006; Monk et al., 2003). Adolescents also exhibit heightened sensitivity to environmental cues (Segalowitz et al., 2010; Somerville et al., 2010). These age-related changes clearly point to the need to understand the profile of oscillatory brain responses to affective stimuli during adolescence.

Our present study examined whether event-related delta and beta oscillations and LPPs, reflect age-related changes in affective processing during adolescence. EEGs were collected from 51 adolescents and 18 undergraduates while they viewed 90 images from the Chinese affective picture system (Bai et al., 2005). The emotional intensity of each picture was then rated. Based on recent LPP investigations in adults and children (Foti and Hajcak, 2008; Hajcak and Nieuwenhuis, 2006; Hajcak and Olvet, 2008; Hajcak et al., 2009; Kujawa et al., 2012), we predicted that the LPP amplitudes elicited by positive and negative images in adolescents would be enhanced relative to neutral pictures. If delta oscillations reflect top-down attention to the motivational relevance of emotional stimuli (Balconi et al., 2009; Klados et al., 2009; Knyazev, 2007, 2012; Knyazev et al., 2009), we predicted that positive and negative pictures would increase delta synchronization compared to neutral pictures. Consistent with previous findings using IAPS pictures (Keil et al., 2007; Güntekin et al., 2010), we predicted that negative pictures would increase beta synchronization compared to positive and neutral pictures. Based on the hypothesis of increasing cortical efficiency (Casey et al., 2000; Rypma, 2007), we predicted that event-related delta and beta synchronization and LPP amplitudes would decrease with age.

2. Methods

2.1. Participants

Sixty-nine right-handed adolescent students and undergraduates were recruited from Shanghai Normal University and four nearby schools in China. All of the participants selected had normal or corrected-to-normal visual acuity and were free of histories of unstable medical illness, head injury, or neurological illness. The participants were classified into four age groups as follows: 12 male and 5 female 12-year-old adolescents in grade 5 from one elementary school (11.78–13.17 years of age), 13 male and 5 female 14-year-old adolescents in grade 8 from two junior high schools (13.75–14.83 years of age), 10 male and 6 female 16-year-old adolescents in grade 11 from one senior high school (15.33–16.67 years), and 10 male and 8 female young adults from undergraduate institutions (18.58–22.08 years of age). All participants, or their guardians if the participants were under 18 years of age, provided written informed consent and were paid approximately $10 for their participation. The relevant institutional ethical committee approved this research.

2.2. Stimulus materials

Participants viewed 90 pictures from the Chinese Affective Picture System (Bai et al., 2005), which is a collection of standardized photographic materials that were obtained from the International Affective Picture System (Lang et al., 1997). Of these images, 30 depicted positive events (e.g., attractive infants, smiling face, and hugging), 30 depicted neutral events (e.g., vegetation, household objects, and buildings), and 30 depicted negative events (e.g., wreckage, a snake, and a horrible face) (Zhang et al., 2013). All image groups differed significantly in the valence dimension [F (2, 87) = 98.32, $p < 0.001$; $M \pm SD$: Positive = 7.42 ± 0.16; Neutral = 4.87 ± 0.08; Negative = 2.23 ± 0.13]. In the arousal dimension, the positive and negative pictures differed from the neutral ones [F (1, 84) = 53.27, 69.57, $p < 0.001$] but did not significantly differ from each other [F (1, 84) = 1.21, $p > 0.05$; $M \pm SD$: Positive = 5.78 ± 00.41; Neutral = 4.69 ± 0.43; Negative = 5.89 ± 0.35]. All images were displayed on a color PentiumIV computer using E-prime 2.0 (Psychology Software Tools, Inc.) to control stimulus timing. Each image was presented in the center of the monitor and encompassed a visual angle of approximately 23 degrees and a viewing distance of approximately 70 cm.

2.3. Procedure

Upon arrival at the laboratory, the participants completed an informed consent form and several questionnaires. Participants then