International Journal of Psychophysiology 112 (2017) 31–39

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Delta-beta coupling is associated with paternal caregiving behaviors during preschool☆

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ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 17 November 2016
Accepted 19 November 2016
Available online 21 November 2016

Keywords:
Delta-beta coupling
Parenting
Preschool
Self-regulation

ABSTRACT

Neural systems that index self-regulation have been associated with mental health outcomes, including risk for anxiety problems, from early in life. Yet, little is known about the environmental factors that may impact the development of neural systems of regulation. Behavioral work suggests that sensitive parenting, or parents' ability to correctly interpret and respond to children's signals, supports the development of regulation. Conversely, harsh parenting, or uninvolved or punitive parent behaviors, is thought to compromise developing regulatory systems. We recorded preschoolers' baseline electroencephalography (EEG) and tested whether individual differences in delta-beta coupling were linked to sensitive or harsh parenting behaviors in mothers and fathers. Using Fisher's *r*-to-*z* transform, we found that preschoolers whose fathers were low (vs. high) in harsh parenting showed greater coupling at parietal electrode sites ($z = 2.66$, $p = 0.00$); preschoolers whose fathers were high (vs. low) in harsh parenting showed greater coupling at frontal electrode sites ($z = -2.14$, $p = 0.02$). Heightened coupling at frontal electrodes was also visible for children who showed high (vs. low) levels of social fear ($z = -2.11$, $p = 0.02$), suggesting that enhanced frontal coupling may be associated with increased risk for anxiety problems. No differences in coupling were seen based on levels of sensitive parenting behaviors in mothers or fathers. Results provide initial evidence that harsh parenting behaviors in fathers are associated with differences in a general index of neural regulation in preschoolers, which may have implications for the development of social fear in early life.

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1. Introduction

Heightened fearfulness (Hirshfeld-Becker et al., 2007; Schwartz et al., 1999; Spence et al., 2001), high, stable levels of social fear (Brooker et al., 2013), and out-of-context displays of fearfulness (Buss et al., 2013) predict increased risk for anxiety problems as early as infancy. These traits are associated with biological and behavioral systems of self-regulation (Degnan et al., 2010; Phelps et al., 2016), disruptions in which may serve as mechanisms of early fear and risk for later disorder. Caregiver behaviors predict observed regulatory behaviors in preschoolers (Rubin et al., 2001). However, it is unclear whether caregiver behaviors similarly disrupt biological systems, impacting self-regulation at a more basic level. Understanding how self-regulation may be impacted at the level of neural activity may provide additional insight into the mechanisms by which the early environment may support or disrupt self-regulation in preschoolers. In the current study, we addressed this gap in the literature by using delta-beta coupling, a purported neural index of self-regulation (Knyazev, 2007; Knyazev and Slobodskaya, 2003), to examine differences in regulatory mechanisms associated with early parenting behaviors. We tested these associations at age 3 years, when neural systems are undergoing vast developmental change and when parents comprise the majority of the child's environment (Kopp, 1982; Tsujimoto, 2008).

1.1. Delta-beta coupling

Noninvasive electroencephalograph (EEG) recordings provide temporally sensitive measures of neural activity. EEG can be used to identify associations between power in different frequency bands and relatively discrete forms of neural processing. For example, low-frequency oscillations in the delta band (0.5 Hz–4 Hz) are positively correlated with motivational, reward and emotional processes in adults (Knyazev, 2007). Greater delta power has been similarly linked to enhanced activity in sub-cortical regions of the brain, including the limbic system, which is believed to underlie emotional and motivational functioning (Gray, 1982; Guyton, 1976). In children, delta (0.5 Hz–2 Hz) is the

☆ We thank the families who participated in this study and the staff members who helped with the recruitment of study participants and data collection. Data collection for this project was supported by K01 MH100240 from the National Institute of Mental Health (PI: Brooker) and P20 GM104417 (PI: Harmsen). The authors have no conflicts of interest to report.

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http://dx.doi.org/10.1016/j.ijpsycho.2016.11.014
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predominant visible frequency in the EEG. However, delta power is also enhanced during periods of emotional processing (Knyazev et al., 2003). Similarly, excessive delta, which may indicate neural immaturity, is visible in children who were more physiologically reactive (Raine et al., 2001) and children with behavioral disorders relative to typically-developing peers (Matsuura et al., 1993). Overall, previous findings suggest that delta is linked, from early in life, to subcortical processes reflecting emotional reactivity.

In contrast, high-frequency oscillations in the beta band are visible during awake states and periods of enhanced cognitive processing in both children (11 Hz–18 Hz) and adults (12 Hz–30 Hz; Bell, 1998; Ray and Cole, 1985; Stern et al., 2001). In adults, beta power is enhanced in contexts that call for attentional control and self-regulation, reflecting intra-cortical connections (Engel et al., 2001; Ray and Cole, 1985). In children ages 8 to 13, beta power is thought to play a similar role in self-regulation: low beta activity is linked to increased impulsivity and diagnosed Attention Deficit Hyperactivity Disorder (Barry et al., 2003; Callaway et al., 1983). Thus, from a behavioral level, beta power appears to be linked to efforts to deploy regulatory behaviors, perhaps by exerting an inhibitory influence on arousal in subcortical systems (Robinson, 1999).

Recently, measures of delta-beta coupling have come of interest as putative indices of associations between reactive and self-regulatory systems. Delta-beta coupling refers to the correlation between neural activity in the delta and beta frequency bands, thus denoting complementary changes in delta and beta power. Although there is not currently a single, agreed-upon definition regarding the functional significance of delta-beta coupling, it is frequently purported to index crosstalk between the brain's cortical and subcortical networks (Knyazev, 2007; Knyazev and Slobodskaya, 2003). From this perspective, delta-beta coupling reflects, in real time, efforts by cognitively-oriented cortical neural networks to downregulate emotion-based reactivity in subcortical networks. Indeed, greater delta-beta coupling, or greater positive correlations between delta and beta power, during resting baseline is associated with trait-level emotion propensities, including enhanced trait anxiety or anxiety symptoms (Knyazev, 2011; Miskovic et al., 2010) and greater trait-level inhibition (Putman, 2011) in adults. Increased baseline coupling is also visible in children of anxious parents (Miskovic et al., 2011a) and preschoolers who are prone to show high levels of fear in low-threat situations (Phelps et al., 2016).

In sum, although the research on delta-beta coupling in children is still in its early stages, evidence suggests that resting baseline delta-beta coupling may index trait-level propensities for cognitively-oriented neural systems to down-regulate neural systems of emotional reactivity. Thus, while we acknowledge that the functional implications of coupling are still being shaped by the expanding literature, we here refer to coupling as “neural regulation” based on the work cited above. Developmental and psychobiological theories suggest that the early environment plays an important role in shaping biological systems of self-regulation. For example, early sensitization theory posits that the early rearing environment programs biological templates for trait-level regulatory responses (Gunnar and Quevedo, 2007; Shirtcliff and Ruttle, 2010). However, few investigations have examined whether neural regulation as indexed by delta-beta coupling might be shaped by the early environment. If so, this neural system may serve as a mechanism by which the early environment affects regulatory capacities and putative risk for later disorder.

1.2. Parenting

Arguably the most prominent environmental mechanisms in early life for typically developing children are interactions with parents. Parent behaviors play an important role in the development of self-regulation (Kopp, 1982) which, in turn, has a significant impact on long-term mental health and well-being (John and Gross, 2004). Research suggests that sensitive and harsh parenting behaviors are particularly salient early influences on children's developing regulatory capacities (Morris et al., 2007). Sensitive parenting, or a parent's ability to correctly perceive, interpret, and respond promptly to children's signals (Ainsworth et al., 1974), positively predicts cognitive abilities (NICHD Early Child Care Research Network, 2003) and emotional regulation (Eisenberg et al., 2003) in offspring. In contrast, greater harsh parenting, or parental uninvolvement, disengagement, or punitiveness (Knutson et al., 2005), is linked to diminished self-regulation, greater social wariness (Degnan et al., 2008), and heightened risk for anxiety problems (Shanahan et al., 2008) during childhood and adolescence.

Studies using Event Related Potentials (ERPs), which measure electrical potentials to isolate quickly-occurring (i.e., on the order of milliseconds) neural processes in response to specific events (e.g., self-monitoring following a button-press response), and functional Magnetic Resonance Imaging (*f*MRI), a measure of the hemodynamic response that measures activation in specific neural structures, have shown that more harsh parenting is linked to hyperactivation of the amygdala (Taylor et al., 2006), and increased sensitivity to errors, (Brooker and Buss, 2014; Meyer et al., 2015), both of which indicate dysregulation and enhanced risk for anxiety problems during childhood. High rates of sensitive parenting, on the other hand, are linked to the healthy development of the corpus callosum, a brain region associated with high order self-regulation (Ghassabian et al., 2013; Kok et al., 2014). However, links between parenting practices and more global assessments of neural regulation remain unexamined, which limits our understanding of the extent to which early parenting behaviors may predict disruptions in general systems of self-regulation. Establishing such associations may be particularly important for children who are unlikely candidates for more specific measures of neural function such as those cited above. Therefore, this was one aim of the current study. We investigated whether the early parental environment – specifically harsh and sensitive parenting - was associated with neural regulation in preschool-aged children. We hypothesized that more parental harshness and less parental sensitivity would be associated with greater efforts at neural regulation, indexed as greater delta-beta coupling, during preschool.

It should also be noted that, to date, much of the work on the role of early parenting in shaping child outcomes has focused on maternal behaviors. However, paternal behaviors may be equally important for child development. For example, greater sensitive parenting in fathers has been associated with better cognitive regulation in children (Towe-Goodman et al., 2014). Greater sensitivity in fathers has also been linked to lower rates of behavioral problems and better social skills during periods of transition (Kazak, 2004), and lower autonomic reactivity in social contexts (Boyce et al., 2006). In contrast, harsher parenting in fathers predicts increased reactivity (Boyce et al., 2006), more aggression (Chang et al., 2003), and a greater risk for mental health issues, including anxiety problems, between ages 7 and 9 (Boyce et al., 2006).

The effects of sensitive and harsh parenting may also rely on the sex of the parent. For example, although greater paternal harshness predicts increased aggression, maternal harshness predicts more problems with emotion regulation (Chang et al., 2003). Furthermore, paternal sensitivity predicts better problem solving skills and autonomy in toddlers and preschoolers even when high rates of mothers' sensitive parenting behaviors are considered (Easterbrooks and Goldberg, 1984; Tamis-LeMonda et al., 2004), suggesting that fathers make independent contributions to developing regulation in children. Thus, a second aim of the current study was to investigate associations between parenting behaviors and neural regulation separately for mothers and fathers. To do this, we tested associations between parenting and delta-beta coupling separately for mothers and fathers in order to understand whether patterns of effects might be similar across parents. We hypothesized that harshness in both mothers and fathers would be associated with enhanced delta-beta coupling.

Finally, we acknowledge that, without additional behavioral evidence, it may be hard to interpret whether links between parenting

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