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Risky decision-making in adolescent girls: The role of pubertal hormones and reward circuitry

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ABSTRACT

Adolescence is a developmental period characterized by a greater tendency to take risks. While the adult literature has shown that sex steroids influence reward-related brain functioning and risk taking, research on the role of these hormones during puberty is limited. In this study, we examined the relation between pubertal hormones and adolescent risk taking using a probabilistic decision-making task. In this task, participants could choose on each trial to play or pass based on explicit information about the risk level and stakes involved in their decision. We administered this task to 58 11-to-13-year-old girls while functional MRI images were obtained to examine reward-related brain processes associated with their risky choices. Results showed that higher testosterone levels were associated with increased risk taking, which was mediated by increased medial orbitofrontal cortex activation. Furthermore, higher estradiol levels were associated with increased nucleus accumbens activation, which in turn related to decreased risk taking. These findings offer potential neuroendocrine mechanisms that can explain why some adolescent girls might engage in more risk taking compared to others.

1. Introduction

1.1. Pubertal hormones and adolescent risk taking

Adolescence, the developmental period between childhood and adulthood, is a dynamic time of transition characterized by dramatic biological, cognitive, social, emotional, and behavioral changes (Dahl, 2004). According to most developmental researchers, the onset of adolescence is marked by puberty (Dorn et al., 2006), a biological process that involves a substantial rise in sex steroids, such as testosterone and estradiol (Shirtcliff et al., 2009; Biro et al., 2014). While the rise in sex steroids during puberty is associated with some of the physical and physiological changes necessary for sexual reproduction, such as the development of secondary sex characteristics, it has also been suggested that pubertal hormones influence the developing adolescent brain (Schulz et al., 2009). As such, pubertal hormones are thought to play an important role in activating the behaviors that characterize adolescents, such as risk taking (Forbes and Dahl, 2010; Peper and Dahl, 2013).

Indeed, adolescent risk taking has been associated with higher levels of testosterone and estradiol, independent of age (De Water et al., 2013; Vermeersch et al., 2008a, 2008b). A neurobiological model proposed to explain increases in risk taking across adolescence emphasizes the role of pubertal hormones in altering subcortical brain functioning, such as reward-related brain activation (Crone and Dahl, 2012). While enhanced reward processing during adolescence, as measured by increased ventral striatum/nucleus accumbens activation compared to children and/or adults, is thought to underlie the tendency to take risks (Galvan, 2010; Somerville et al., 2010; Steinberg, 2010), the influence of pubertal hormones on reward processing often remains untested. Thus, relatively few studies have concomitantly captured data related to hormone levels, brain activity, and risk-taking behavior.

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Importantly, in addition to developmental influences, individual differences in risk taking tendencies resulting from genetic (Harden and Mann, 2015) and/or personality differences (Braams et al., 2015; Van Duijvenvoorde et al., 2014) likely contribute to differences in adolescent risky behavior (and associated brain activation). Moreover, these individual and developmental differences are likely to interact across adolescent development, meaning that developmental changes might result in different behavioral and/or neural phenotypes depending on genetics or personality characteristics. These findings suggest that individual differences in adolescent risk taking (and associated brain processes) reflect both developmental and individual differences (Chick, 2015), which might both be captured by individual differences in pubertal hormone levels.

1.2. Pubertal hormones and reward-related neural processes

To date, few longitudinal neuroimaging studies have shown that structural changes in subcortical brain regions involved in reward processing, such as the nucleus accumbens, are related to pubertal stage (Goddings et al., 2014) and pubertal hormone levels (Peper et al., 2011; Herting et al., 2014), and these findings have not been consistent in all studies (Koolschijn et al., 2014). In addition to structural changes, functional changes in reward-related brain regions have also been reported, including enhancing effects of testosterone and estradiol administration on reward processes associated with risk taking in adults (Hermans et al., 2010; Thomas et al., 2014). However, evidence for the role of hormones in subcortical brain functioning during puberty is both limited and conflicting (Forbes et al., 2010; Op de Macks et al., 2011; Braams et al., 2015).

In a prior cross-sectional study, we began to address this gap by using a newly designed probabilistic decision-making task called the Jackpot task. In this task, participants chose to play or pass based on presented information about the chance of winning 10 Eurocents (Op de Macks et al., 2011). By administering this task to a sample of 33 girls and 17 boys (10–16 yrs), we demonstrated that higher levels of testosterone corresponded with enhanced ventral striatum activation when a risky decision was rewarded, whereas higher levels of estradiol corresponded with more frontal activation, although the estradiol findings were weaker (Op de Macks et al., 2011). A similar finding resulted from a longitudinal study on reward processing among 8–27 year-olds, whereby changes in nucleus accumbens activation in response to reward receipt correlated with changes in testosterone level (Braams et al., 2015). In contrast, a cross-sectional study of 39 girls aged 11–12 years who played a card-guessing game found a *reduced* striatal response to rewards in girls with higher levels of testosterone (Forbes et al., 2010). These latter studies did not report on the relation between estradiol level and reward-related brain activation. More importantly, these studies focused on the relation between testosterone and brain processes involved in decision-making, but did not test the three-way relation between testosterone level, reward-related brain processes, and associated risk-taking behavior.

Additionally, relatively less is known about hormonal influences on other components of the reward system, including areas within the medial frontal cortex that are linked to valuation (O'Doherty, 2007). Specifically, the ventromedial prefrontal cortex, or medial orbitofrontal cortex, is considered part of the "reward circuit" given its anatomical connections with other reward-related brain regions (e.g., ventral striatum, including nucleus accumbens) and its responsiveness to both primary and secondary rewards (Haber and Knutson, 2010). More importantly, anatomical differences in the medial orbitofrontal cortex have been shown to mediate the relation between testosterone level and risk taking on the balloon analogue risk-taking (BART) task in adolescent boys and girls (Peper et al., 2013). However, the implications of structural differences for reward-related brain functioning remain unknown. Furthermore, orbitofrontal cortex activation during reward anticipation has been shown to differ across the menstrual cycle in adult women (Dreher et al., 2007) and ventromedial prefrontal cortex activation has been shown to increase upon estradiol administration in postmenopausal women (Thomas et al., 2014). Together, these findings suggest that the rise in sex steroids during puberty might enhance reward processing in medial frontal regions, in addition to subcortical regions.

1.3. The present study

To directly test the three-way relation between pubertal hormone levels, reward-related brain functioning, and risky behavior, we designed a study to examine the relation between levels of testosterone as well as estradiol and risk taking, and to test whether this relation was mediated by increased reward-related (cortical and subcortical) brain activation. Furthermore, to optimize our ability to test these relations independent of age within a cross-sectional design, we focused on a narrow age range around the onset of puberty to capture the developmental window during which individual differences in pubertal hormone levels are the largest – given the large individual variation in the onset and speed of pubertal changes – while keeping age relatively constant (Dorn et al., 2006; Peper and Dahl, 2013). We used a modified version of the Jackpot task based on Op de Macks et al. (2011) in which, in addition to manipulating the *probability* of reward, we also manipulated the *magnitude* of the potential reward (i.e., stakes). The study that used the previous version of the Jackpot task, as well as other studies that used a decision paradigm with the same probabilities (33% vs. 67%), have shown that adolescents more often made risky decisions when the chance to win was higher and engaged in riskier decisions when stakes were higher (Op de Macks et al., 2011; Van Leijenhorst et al., 2008, 2010). Therefore, we aimed to increase possibilities for risk taking (e.g., when the chance to win was relatively low but the potential reward was relatively large) and thereby optimize our ability to investigate reward-related brain processes associated with risky decisions. Besides the types of decisions adolescents made, we also examined decision speed, which has been shown to vary by stakes (but not by probability), such that decision speed decreased with increasing stakes (Van Leijenhorst et al., 2010). Based on these findings, we hypothesized that adolescents in this study would show greater risk taking in the low-risk condition and when a larger reward was at stake. Furthermore, we hypothesized that adolescents with higher testosterone and estradiol levels would show increased risk taking (Vermeersch et al., 2008a, 2008b), particularly in the high-risk condition, as adolescents showed greater individual variation in the propensity to take risks within this condition (Op de Macks et al., 2011).

We focused on individual differences in activation of nucleus accumbens (Haber and Knutson, 2010), a region known to be involved in reward anticipation and/or outcome processing and often reported to show increased activation in adolescents compared to children and adults in the context of risky decision-making (reviewed in Galvan, 2010). Concomitantly, to ensure that behaviorally-relevant activation within other regions of the reward circuit would be captured, we also conducted whole-brain analyses that included the medial frontal cortex. We hypothesized that nucleus accumbens activation would be elevated during risky decisions (Op de Macks et al., 2011). Furthermore, we predicted that the relation between pubertal hormones and risk taking would be mediated by increased reward-related brain activation (according to the model proposed by Crone and Dahl, 2012).