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Increased functional connectivity with puberty in the mentalising network involved in social emotion processing

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ABSTRACT

This article is part of a Special Issue "Puberty and Adolescence".

There is increasing evidence that puberty plays an important role in the structural and functional brain development seen in adolescence, but little is known of the pubertal influence on changes in functional connectivity. We explored how pubertal indicators (salivary concentrations of testosterone, oestradiol and DHEA; pubertal stage; menarcheal status) relate to functional connectivity between components of a mentalising network identified to be engaged in social emotion processing by our prior work, using psychophysiological interaction (PPI) analysis. Female adolescents aged 11 to 13 years were scanned whilst silently reading scenarios designed to evoke either social emotions (guilt and embarrassment) or basic emotions (disgust and fear), of which only social compared to basic emotions require the representation of another person's mental states. Pubertal stage and menarcheal status were used to assign participants to pre/early or mid/late puberty groups. We found increased functional connectivity between the dorsomedial prefrontal cortex (DMPFC) and the right posterior superior temporal sulcus (pSTS) and right temporo-parietal junction (TPJ) during social relative to basic emotion processing. Moreover, increasing oestradiol concentrations were associated with increased functional connectivity between the DMPFC and the right TPJ during social relative to basic emotion processing, independent of age. Our analysis of the PPI data by phenotypic pubertal status showed that more advanced puberty stage was associated with enhanced functional connectivity between the DMPFC and the left anterior temporal cortex (ATC) during social relative to basic emotion processing, also independent of age. Our results suggest increased functional maturation of the social brain network with the advancement of puberty in girls.

Introduction

During adolescence, major changes in social and cognitive behaviours take place (Spear, 2000). Changes in social behaviours include increased focus on peer relationships and development of social skills required for more complex social relations (Steinberg and Morris, 2001). It has been proposed that many of these changes are partly due to the effects of puberty – and associated increased hormone levels – on the human brain (Blakemore et al., 2010; Forbes and Dahl, 2010). Puberty, the biological process of increased gonadal steroid hormone secretion resulting in reproductive competence, occurs between the ages of 8 and 14 years in females, and 9 and 15 years in males (Tanner, 1962). The steroid hormones involved in puberty, particularly testosterone and oestradiol, have been shown to influence brain maturation in animal models (Sisk and Zehr, 2005). Recently, studies in humans have shown effects of puberty, independent of the effects of age, on neural responses in reward-related tasks (e.g., Forbes et al., 2010), emotion processing (Moore et al., 2012) and social emotion processing (Goddings et al., 2012). The aim of the current study was to examine the effects of puberty on *functional connectivity* within a mentalising network identified to be engaged in social emotion processing by our prior work (Burnett and Blakemore, 2009).

In a previous functional magnetic resonance imaging (fMRI) study (Goddings et al., 2012), we investigated the effects of puberty on the blood oxygenation-level dependent (BOLD) signal within a particular social brain component, the 'mentalising network', comprising the

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dorsomedial prefrontal cortex (DMPFC), the posterior superior temporal sulcus (pSTS) at the temporo-parietal junction (TPJ) and the anterior temporal cortex (ATC) (Frith and Frith, 2003). Mentalising – the ability to understand another person's intentions, emotions, desires and beliefs – is a crucial capacity for a range of social behaviours and depends on important components of the social brain network (Olsson and Ochsner, 2008). In our previous study, 42 girls within a narrow age range in early adolescence (11.1–13.7 years) were divided into two groups according to stage of puberty (pre/early vs. mid/late) and also provided salivary sex hormone assays (testosterone, oestradiol, and dehydroepiandrosterone (DHEA)). BOLD signal was recorded whilst participants silently read scenarios designed to evoke either social emotions (guilt and embarrassment) or basic emotions (disgust and fear). Across the entire group, the social brain network was activated when social emotion processing was contrasted with basic emotion processing. In addition, there were functionally dissociable effects of pubertal hormones and chronological age on the mentalising network. Increasing sex hormone levels (independent of chronological age) were associated with increasing BOLD signal in the left ATC during social emotion processing. Increasing age (independent of hormone levels) was associated with decreasing DMPFC activity during social emotion processing (Goddings et al., 2012).

Several neuroimaging studies of mentalising have found a similar *age-related* decrease in DMPFC activity during adolescence into adulthood (e.g., Burnett et al., 2009; Gunther Moor et al., 2011; Pfeifer et al., 2009; Wang et al., 2006). These studies often report age-related increases in activity in other parts of the mentalising network (pSTS/TPJ and ATC) during this period. In addition to functional changes during mentalising tasks in adolescence, there are also structural changes in the social brain network during this period of life (Mills et al., 2012). In terms of behavioural development, a previous study demonstrated pubertal development in the appreciation of mixed emotions for social compared with basic emotion processing (Burnett et al., 2011). Furthermore, speed of mentalising has been found to increase with age during adolescence (Keulers et al., 2010) and the same study found that pubertal phase in boys aged 12–15 contributed independently to mentalising speed after controlling for age. Finally, the ability to take into account another person's perspective in order to guide appropriate decisions and actions is still improving during mid-late adolescence (Dumontheil et al., 2010).

Whilst several studies have investigated mentalising in adolescence, and the effect of puberty on mentalising, no previous studies have investigated how puberty influences connectivity between brain regions within the social brain network. In the current study, we investigated the effect of puberty on functional connectivity between brain regions within a mentalising network identified to be engaged in social emotion processing by our prior work (Burnett and Blakemore, 2009) during the social emotion paradigm.

Previous developmental functional and effective connectivity studies

Developmental changes in functional connectivity – that is, correlated activity between brain regions during "resting state", or during one psychological task relative to another – have been reported in a growing number of studies. Time perception, spelling and scene retrieval studies show age-related increases between childhood and adulthood in functional connectivity between regions focally associated with task performance (Booth et al., 2008; Ofen et al., 2012; Smith et al., 2011). Successful response inhibition, as assessed using the Go/No-go task, shows patterns of both increasing and decreasing functional connectivity with age in adolescence, depending on the particular region and the functional network examined (Keulers et al., 2012; Stevens et al., 2007). In a study that employed a probabilistic learning task, increasing age during adolescence was associated with increased functional connectivity between the striatum and medial prefrontal cortex during positive relative to negative performance feedback (Van den Bos et al., 2011).

In "resting-state" functional connectivity studies, which often examine large-scale connectivity patterns across the brain, a consistent finding is that functional connectivity between spatially distant, functionally-related brain regions increases between childhood and adulthood, whilst connectivity between more spatially proximal regions decreases (e.g., Dosenbach et al., 2010; Fair et al., 2008; Fair et al., 2009; Qin et al., 2012; for a review see Vogel et al., 2010). Resting-state functional connectivity is modulated by serotonin transporter genotype (Wiggins et al., 2012), stress-induced activation of the hypothalamic–pituitary–adrenal axis (Thomason et al., 2011) and oestrogen level in adult females (Ottowitz et al., 2008a, 2008b).

Relatively few developmental studies have examined functional connectivity during social cognition tasks. Studies investigating face processing show evidence for age-related increases in functional connectivity in the core face processing network between childhood and adulthood (Cohen Kadosh et al., 2011), and in networks mediating the impact of prior expectations on the processing of emotional faces between adolescence and adulthood (Barbalat et al., 2012). A longitudinal fMRI study showed adolescent age-related increases in functional connectivity between action observation and social brain regions during observation of angry versus neutral hand gestures, in males but not in females (Shaw et al., 2011). Previously, we have shown an age-related *decrease* between adolescence and adulthood in task-dependent functional connectivity between the DMPFC and the pSTS/TPJ (Burnett and Blakemore, 2009). To the best of our knowledge, previous developmental studies have not explored potential relationships between puberty measures and functional connectivity during social cognitive tasks. In our previous developmental functional connectivity study (Burnett and Blakemore, 2009) no pubertal measures were acquired; thus it is unknown whether functional connectivity between regions within this mentalising network is influenced by pubertal development. However, it is increasingly recognised that pubertal hormones organise structural brain connectivity in humans (Peper et al., 2011a). Given the evidence for gender-specific patterns of adolescent functional connectivity during social cognition (Shaw et al., 2011), and evidence for an impact of female gonadal hormones on functional connectivity in adults, investigating this relationship could be fruitful.

The current study

In the current study, we performed a psycho-physiological interaction (PPI) analysis to explore functional connectivity between the DMPFC and the other regions of a mentalising network identified to be engaged in social emotion processing by our prior work (Burnett and Blakemore, 2009), using data from a previously reported sample (Goddings et al., 2012). PPI analysis examines the association between BOLD signals in particular brain regions in one psychological context (experimental condition) compared with another (Friston et al., 1997; O'Reilly et al., 2012). We chose the DMPFC as a source region in accordance with our previous PPI analysis of the same task in another sample (Burnett and Blakemore, 2009) and its general role in mentalising (Amodio and Frith, 2006). In the current study, three independent measures of puberty were obtained from female participants aged 11.1–13.7 years: salivary hormone assays for testosterone, oestradiol and DHEA; visual clinician assessment of Tanner stage (Marshall and Tanner, 1969); and a self-report measure of menarcheal status. We explored how functional connectivity within a mentalising network identified to be engaged in social emotion processing by our prior work relates to these measures of puberty.

Methods

Participants

42 female adolescents aged 11.1 to 13.7 years (mean 12.5; SD 0.7) participated in this study. Here, we report data from N = 35