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How do expectant fathers respond to infant cry? Examining brain and behavioral responses and the moderating role of testosterone

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Abstract

Expectant parents' responses to infant cry may indicate future risk and resiliency in the parent-child relationship. Most studies of parental reactivity to infant cry have focused on mothers, and few studies have focused on expectant fathers, although fathers make important contributions to parenting. Additionally, although different responses to infant cry (behavioral, psychological and neural) are hypothesized to track together, few studies have analyzed them concurrently. The current investigation aimed to address these gaps by characterizing multimodal responses to infant cry within expectant fathers and testing whether prenatal testosterone moderates these responses. Expectant fathers responded to infant cry *vs* frequency-matched white noise with increased activation in bilateral areas of the temporal lobe involved in processing speech sounds and social and emotional stimuli. Handgrip force, which has been used to measure parents' reactivity to cry sounds in previous studies, did not differentiate cry from white noise within this sample. Expectant fathers with higher prenatal testosterone showed greater activation in the supramarginal gyrus, left occipital lobe and precuneus cortex to cry sounds. Expectant fathers appear to interpret and process infant cry as a meaningful speech sound and social cue, and testosterone may play a role in expectant fathers' response to infant cry.

Key words: infant cry; response; fathers; physiological; behavioral; cognitive; affective

Introduction

An infant's survival depends on the caregiving relationship. Caregivers who respond sensitively to their infant's needs can facilitate their child's healthy development (Ainsworth, 1979; Malmberg *et al.*, 2016). An infant's primary form of communication, crying, may arouse the parent to respond and attend to an infant's distress (Brosch *et al.*, 2007). Researchers have studied endocrine, behavioral and, more recently, neural responses to infant cry, finding that hormone levels, handgrip strength and patterns of brain activation may vary while listening to infant cries (Fleming *et al.*, 2002; Crouch *et al.*, 2008; Kim *et al.*, 2010). Previous studies have suggested that calm parental responses to

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cry may be linked with approach-oriented, sensitive responses to infants (e.g. Joosen *et al.*, 2013), whereas irritated or hyper-reactive responses may be linked with risk for aggression or neglect (Reijman *et al.*, 2014; Zeifman and St James-Roberts, 2017).

Despite these intriguing findings, the literature on reactivity to infant cry has several notable gaps. Surprisingly, given that fathers often participate in infant caregiving, few studies have investigated responses to infant cry sounds in fathers and even fewer have included expectant fathers (Thijssen *et al.*, 2018; Alyousefi-Van Dijk *et al.*, 2019). Interventions have targeted parents' possible responses to infant cry as a marker of aggressive responses to a crying infant (Barr *et al.*, 2009; Coster, 2017). However, it is imperative to thoroughly study expectant fathers' responses to infant cry in order to best tailor these interventions specifically before the baby even arrives. Men's hormones prior to the birth of their child (e.g. their testosterone levels during their partner's pregnancy) may also reflect their preparation for parenting (Saxbe *et al.*, 2017a) and also warrant examination in conjunction with expectant fathers' responses to infant cry. Lastly, although responses across different measurement domains, such as brain and behavioral responses, are assumed to relate to one another (Messina *et al.*, 2016), few studies have measured multiple responses to cry sounds within the same population and analyzed them concurrently (e.g. Riem *et al.*, 2012). Understanding how behavior works in tandem with the brain will help to clarify an overarching theory of the biological response to infant cry and identify where this system may go awry in aggressive or abusive parenting responses.

The current investigation aims to address these gaps by characterizing behavioral, psychological and neural responses to infant cry compared to frequency-matched white noise within expectant fathers and by testing whether paternal prenatal testosterone, a hormone that may reflect paternal investment, affects reactivity to infant cry.

Neural responses to infant cry

Studies of parental brain responses to infant cry have focused primarily on mothers, with few studies on fathers and even fewer investigating expectant fathers (for review see Lynch, 2003; Rilling and Young, 2014; Feldman, 2015; Abraham and Feldman, 2018; Thijssen *et al.*, 2018; Witteman *et al.*, 2019). These studies have investigated how parents respond to own infant cry *vs* unfamiliar infant cry or an unfamiliar infant cry compared to a control sound. Infant cry sounds, in comparison to video or picture stimuli of infants, have been linked with amygdala activation in mothers, but not fathers or non-parents (Feldman, 2015). Recruitment of the amygdala may underscore parental vigilance to infant distress cues (Abraham *et al.*, 2014). Studies have found that mothers listening to an unknown infant compared to a frequency-matched white noise show activation in components of the midbrain dopamine system (i.e. substantia nigra and ventral tegmental area), anterior and posterior cingulate cortex, right fronto-insular cortex, dorsomedial pre-frontal cortex (dMPFC) (regions involved with emotional and cognitive empathy) and right lateralized auditory cortices extending to the temporal pole (Lorberbaum *et al.*, 1998). A study of neural reactivity in first-time fathers listening to unknown infant cry compared to a white noise control found bilateral activations in the medial pre-frontal cortex, bilateral anterior insula and inferior frontal gyrus (IFG), bilateral striatum, bilateral thalamus, bilateral auditory cortex (including the planum temporale, Heschl's gyrus and supramarginal gyrus) bilateral posterior cingulate and bilateral midbrain structures (Li *et al.*, 2018). No differences were found between own infant cry and unfamiliar infant cry in these first-time fathers. Similarly, a study of the effects of vasopressin on processing infant cry sounds in expectant fathers found that infant crying (*vs* control sounds) was associated with increased activation in the bilateral auditory cortex and posterior medial cortex (Thijssen *et al.*, 2018). First-time fathers, similarly to first-time mothers, appear to engage five neural systems while listening to unknown infant cries: (i) auditory cortex (auditory perception), (ii) dMPFC (perspective-taking, theory of mind), (iii) fronto-insular cortex (emotional empathy), (iv) thalamocingulate circuits (parental caregiving) and (v) midbrain dopaminergic regions (approach motivation) (Feldman, 2015). A recent meta-analysis similarly confirmed involvement of the cingulate, the auditory system, the pre-supplementary motor area, the dorsal anterior insula, the dMPFC and the IFG in infant cry perception as well as larger activations in the right IFG, temporal pole and left angular gyrus in men in response to infant cry compared to women (Witteman *et al.*, 2019).

Handgrip modulation response to infant cry

Modulation of handgrip force is interpreted as a behavioral indicator of motivation to respond to the distressed infant (Crouch *et al.*, 2008; Riem *et al.*, 2012; Zeifman and St James-Roberts, 2017). The ability to modulate handgrip force is measured by a dynamometer, which tracks grip strength while an individual listens to an infant crying. Studies have suggested that excessive handgrip force, referred to as 'poor modulation', may indicate risk for abuse or aggressive responding toward an infant (Bakermans-Kranenburg *et al.*, 2012). Poorly modulated handgrip response to infant cry has been linked with neglectful and physically abusive mothers (Compier-de Block *et al.*, 2015) and with parents at risk for child physical abuse (Crouch *et al.*, 2008). Other studies suggest that poor modulation of handgrip may be an indicator of motivation to act or help while an infant is crying (Parsons *et al.*, 2013). One study of expectant fathers failed to find a difference in handgrip modulation between infant cry and frequency-matched white noise control sounds (Alyousefi–Van Dijk *et al.*, 2019). However, this study involved vasopressin administration and viewing pictures of infant faces while listening to infant cry. Earlier studies of infant cry and handgrip force also rarely utilized control sound stimuli, making it difficult to assess whether poor modulation is tied specifically to infant cry or more broadly to any distressing sound. The current study builds on previous studies in examining the response to infant cry in expectant fathers while also using a control condition of frequency-matched white noise.

Psychological response to infant cry

In addition to neural and behavioral responses to infant cry, researchers have investigated individual differences in parents' self-reported interpretations of infant cry. Interpretations of a crying infant as intentionally hostile or reporting increased frustration and negative emotion while listening to infant cry have been associated with risk for aggressive or harsh parenting behaviors (Crouch *et al.*, 2008; Rodriguez *et al.*, 2015). However, the question of whether these interpretations are associated with neural or behavioral responses to cry sounds is underexplored. Parents who rate infant cry sounds as more hostile may show more excessive handgrip force while listening to infant cry (Crouch *et al.*, 2008). Similarly, one study found that fathers

who rated infant cry as more aversive exhibited greater neural activation in auditory cortices (Li *et al.*, 2018). Li and authors interpreted this greater neural activation as reflecting a form of negative emotional overarousal in response to infant cry sounds. However, another study found no relationship between mothers' irritation with infant cry sounds and their neural responses to the same sounds (Riem *et al.*, 2012). In sum, this literature is small and inconclusive and has generally not included expectant fathers.

The role of testosterone

Many recent studies have investigated the neuroendocrine underpinnings of parenting (Bos *et al.*, 2010; Bos, 2017). Testosterone appears to decline across the transition to parenthood in men and may be associated with paternal sensitivity and involvement in childcare (Gettler *et al.*, 2011; Storey and Ziegler, 2016; Saxbe *et al.*, 2017b). Infant cry can elicit sensitive caregiving (Murray, 1985) or frustration and annoyance (Frodi, 1985; Barr *et al.*, 2006; Del Vecchio *et al.*, 2009). Some parents may be physiologically overly responsive to noxious child stimuli, such as infant cry (Knutson, 1978). This hyperreactivity can lead to an increase in 'irritable aggression,' which may reflect heightened parenting stress and compromised parent-child bonding.

Higher levels of T around the transition to parenthood may indicate the potential for harsh or insensitive parenting, particularly when coupled with this hyperreactivity to infant cry. The role of testosterone in modulating paternal responses to infant cry, however, has received little attention, with most studies focusing on T reactivity to infant stimuli rather than baseline levels of T across the transition to parenthood. One of the only studies to investigate baseline levels of T in first-time fathers (post-partum) failed to find a relationship between baseline T levels and neural activation differences in response to infant cry *vs* frequency-matched white noise (Li *et al.*, 2018). In studies investigating T reactivity to infant cry, it has been found that men with higher T reactivity (non-fathers and new fathers) in response to unfamiliar infant cries show less sympathy for these infant cries (Fleming *et al.*, 2002). Another study of reactivity to infant cry video stimuli found greater activation in the left caudate in fathers whose testosterone increased more after interacting with their child (Kuo *et al.*, 2012). These authors suggest that increased testosterone and greater neural activation may indicate the body readying itself to protect the baby as signaled by the urgent cries (Kuo *et al.*, 2012). Additionally, another study found that infant cries from a baby doll decreased T levels when the father was allowed to care for the infant but increased T levels when the father was blocked from nurturing the infant (Van Anders *et al.*, 2012), while another found lower T after interacting with an infant in fathers with low cortisol levels (Bos *et al.*, 2018). Therefore, context may be important for understanding the relationship between T and infant cry reactivity in fathers, and increased T levels (both baseline and reactivity) may indicate a physiological hyperreactivity to infant cry and be associated with other potential hyperactive responses to infant cry such as neural activity and handgrip modulation. Notably, testosterone level appears to be positively associated with handgrip strength in men (Gallup *et al.*, 2010), but the relationship between testosterone and handgrip modulation has not been thoroughly tested in the context of infant cry. Few studies have investigated testosterone levels in expectant fathers before the birth of their child (prenatal T) and its potential role in reactivity to infant cry.

Current study

Although neural, behavioral and psychological responses to infant cry have been examined separately in previous studies, multi-modal approaches are needed to characterize how and whether these responses are correlated across domains. Moreover, understanding how expectant fathers respond to infant cry, and the role of testosterone in shaping these responses, might elucidate how fathers transition to parenthood and prepare to care for their infants.

Within a sample of fathers expecting their first child, we tested four hypotheses:

(i) In response to infant cry sounds (*vs* white noise), we expected that expectant fathers would show greater neural activation in regions that have been associated with infant cry specifically (e.g. socio-cognitive areas such as the STG, insula, mPFC, dlPFC, auditory cortices and IFG). We planned to use whole-brain analyses to test this hypothesis and to supplement these analyses with an a priori ROI focused on the amygdala.

(ii) We also expected fathers to show behavioral responses to infant cry sounds, specifically poor handgrip modulation when listening to infant cry sounds compared with white noise sounds.

(iii) We expected that fathers' responses to infant cry would be consistent across neural, behavioral and self-report modalities. Specifically, given evidence that fathers who rated infant cry more negatively also showed heightened neural activation to cry (Li *et al.*, 2018), we expected that fathers who showed greater neural activation to infant cry in hypothesized brain areas would also show poorer handgrip modulation, greater interpretation of the infant as more negative during infant cry and greater self-reported negative emotions after infant cry compared to white noise.

(iv) Given that prenatal testosterone may reflect paternal investment in sensitive parenting, which requires the ability to modulate negative responses to aversive stimuli such as infant cry, we hypothesized that fathers with higher prenatal testosterone levels would show more reactivity to infant cry, including more negative ratings of the infant, more negative emotions after listening to infant cry, poorer handgrip modulation and more activation in hypothesized brain areas in response to infant cry.

Methods

Participants

Participants were drawn from the larger longitudinal Hormones and Attachment Across the Transition To Childrearing (HATCH) study. The study follows couples from mid-to-late pregnancy across the first year post-partum. Recruitment occurred via flyers, social media advertising and word of mouth. The current study uses data from a prenatal laboratory visit, conducted in mid-to-late pregnancy, and a separate MRI visit that occurred within 2 weeks of the in-lab visit. Inclusion criteria included that couples were cohabiting, pregnant for the first- time with a singleton fetus and free of use of psychotropic medication. Exclusion criteria included any contraindications for MR scanning, the use of psychotropic medication and left-handedness.

Data for the current study were available for 41 expectant fathers who provided handgrip and self-report data. Of these, 34 fathers also provided neuroimaging data, and 32 of these fathers provided testosterone data. Mean age was 31.7 years

old (s.d. = 4.25 years). The sample was highly educated with 80% of participants achieving a college degree or higher, and the population was ethnically diverse (36% White, 7% Black, 26% Hispanic or Latin, 24% Asian or Pacific Islander and 5% others).

Procedure

Expectant fathers participated in one in-lab visit scheduled mid-to-late pregnancy (average weeks pregnant = 29 weeks, s.d. = 4.7 weeks, range = 18–38 weeks) and an MRI visit an average of 1.05 (s.d. = 1.04, range 0–4 weeks) weeks later. The majority of fathers (31 out of 34 fathers) completed the scan visit within 2 weeks of the in-lab visit. During the prenatal in-lab visit, each father provided three saliva samples for testosterone sampling over 90 minutes and completed the handgrip task after saliva collection, as described below. Additionally, after completing the handgrip task, fathers were asked to listen to the infant cry noise and complete the Emotional Reactions Questionnaire (ERQ) and trait rating task. During the MRI visit, fathers completed the same infant cry task as part of a larger MRI data collection protocol. All procedures were approved by University IRB, and all participants signed informed consent forms prior to participation.

Infant cry task. Using the same infant cry and control sounds as a previous study (Riem *et al.*, 2014), the cry task included six 30-second auditory clips of infant crying interspersed with six 30-second clips of frequency-matched white noise counterbalanced across participants leading to 12 trials. The stimuli were presented electronically using the E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) in a block design. The task was 6-minute long and administered in one run.

Handgrip modulation. Established procedures for handgrip dynamometer data collection (Crouch *et al.*, 2008; Bakermans-Kranenburg *et al.*, 2012; Riem *et al.*, 2012) were followed. Prior to playing the infant cry task, a research assistant demonstrated correct hand placement on the dynamometer and modeled the handgrip task (with their dominant hand). Participants watched a line graph indicating grip-strength on the computer screen. The participant was asked to perform a full-strength squeeze and a half-strength squeeze while watching the line graph. The RA gave verbal feedback on each trial to demonstrate an accurate full-strength and half-strength grip. Once the participant performed this task accurately for three consecutive trials, the participant performed the infant cry task. During data collection, participants were prompted to do a full-strength squeeze, followed 2 seconds later by a half-strength squeeze one time per infant cry and white noise trial. Participants averaged 30 trials (of one full-strength grip and one half-strength grip) during training, with a range of 7–50 trials to master the task.

Testosterone. Saliva samples were collected in CryoSafe collection tubes using passive drool and then stored at −80°C before shipment on dry ice to the Technical University of Dresden (Kirschbaum, PI) to be assayed. Fathers were instructed not to eat, drink anything besides water and chew gum within an hour of before collection. Timing of collection was held constant across participants to minimize variability, and testosterone samples were taken during the first 90 minutes of the prenatal laboratory visit and were not concurrent with the handgrip task described above which occurred after all saliva samples were collected. Testosterone levels were averaged across the three samples.

Neuroimaging protocol. Imaging was performed on a Siemens 3 Tesla MAGNETOM Prisma scanner using a 20-channel matrix head coil. Functional images were collected using a T2*-weighted echo planar (EPI) sequence (32 transversal slices; TR = 2000 ms; TE = 25 ms; flip angle = 90°) with a voxel resolution of 3 mm × 3 mm × 2.5 mm. Anatomical images were acquired using a magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence (TR = 2530 ms; TE = 3.13 ms; flip angle 10°; isotropic voxel resolution 1 mm^3). Task sounds were transmitted using Siemens V14 sound headphone system.

Measures

Emotional reactions questionnaire. Following the in-lab cry task, participants completed the ERQ (Milner *et al.*, 1995) to indicate how well each adjective describes their present mood (1, not at all, to 7, extremely well). The negative emotion (bothered, irritated, annoyed and hostile) subscales were averaged to determine negative emotions after listening to infant cry (alpha = 0.95, Milner *et al.*, 1995).

Trait rating task. Also following the in-lab infant cry task, each father was asked to rate the infant on nine traits (i.e. hostile, negative, difficult, friendly, cooperative, sweet, content, lively, attached). Following the procedures of previously conducted studies (Crouch *et al.*, 2008; Bakermans-Kranenburg *et al.*, 2012), the trait ratings were made on a 10-point scale (ranging from 1, not at all, to 10, extremely likely). Positive traits were also included to increase validity and decrease bias toward negative traits. Trait ratings were averaged across the three negative traits (hostile, negative and difficult) to obtain a composite negative trait rating.

Analyses

Hypothesis 1. Neural responses to infant cry were analyzed using FEAT (FMRI Expert Analysis Tool) of FSL (FMRIB's Software Library, www.FMRIb.ox.ac.uk/fsl; Smith *et al.*, 2004). First, motion correction using MCFLIRT, non-brain removal, spatial smoothing (5 mm FWHM Gaussian kernel) and registration to T1-weighted images using FSL FLIRT were done for pre-processing. Then, functional activation was examined with general linear model analyses. To identify regions involved in the perception of infant crying, contrasts of cry > white noise and white noise > cry were assessed. Contrasts of parameter estimates (COPEs) for cry > white noise and white noise > cry sound tested primary hypotheses regarding response to infant cry *vs* a frequency-matched white noise. First-level COPEs served as inputs to higher-level group analyses conducted using FLAME to model random-effect components of mixed-effect variance. Images were thresholded with clusters determined by $Z > 2.3$ and a cluster-corrected significance threshold of $P < 0.05$ (Worsley *et al.*, 2002) to identify regions that were activated during cry *vs* white noise across the six blocks for each sound. Father's age and weeks pregnant were mean-centered and included as confound regressors in all models. Models were run with and without covariates and yielded similar results. To visualize results, spherical ROIs ($r = 5$ mm) centered on activation peaks were used to extract signal change for each condition.

Additionally, given our a priori hypotheses focusing on the amygdala, ROI analyses of the bilateral amygdala were conducted. Parameter estimate values were converted to percentage signal change values via scaling of the PE or COPE values by (100*) the peak-peak height of the regressor (or effective regressor in

Table 1. Means and standard deviations for study variables

	N	Mean (s.d.)
Average handgrip cry	39	0.584 (0.124)
Average handgrip control	40	0.597 (0.126)
ERQ	39	11.28 (5.77)
Trait rating task	39	4.93 (2.17)
Aggregate testosterone	33	56.61 (20.65)
Age of expectant father	41	31.70 (4.25)
Days pregnant at prenatal visit	41	205.80 (33.01)

the case of COPEs) and then by dividing by the mean over time of the filtered functional data. A report was generated using featquery with statistics derived from each image's values within the mask. Percent signal change was extracted from bilateral amygdala using anatomically defined masks created using the Harvard-Oxford subcortical atlas.

***Hypothesis* 2.** Consistent with previous studies (Crouch *et al.*, 2008; Bakermans-Kranenburg *et al.*, 2012; Riem *et al.*, 2012), handgrip modulation was calculated by dividing the half-squeeze intensity by the maximum squeeze intensity per block, and an average ratio of half strength/full strength squeezes was calculated for infant cry and white noise per person.

***Hypothesis* 3.** Demeaned self-report ratings of infant cry and negative emotions were added (separately) as regressors into the general linear model described above. The first-level contrast images of cry > white noise and white noise > cry were submitted to second-level whole-brain analysis to determine differences in activation depending on interpretations of the infant as more negative and self-reported negative emotions after infant cry. Both positive and negative contrast weights were tested for each continuous predictor to determine whether it is related to increased or decreased neural response. Lastly, multivariate regression analyses were used to test the relationship between interpretations of the infant as more negative, and negative emotions during infant cry and signal change in the amygdala ROI.

***Hypothesis* 4.** First, testosterone was added as a regressor to the FSL models testing the relationship between prenatal T and neural activation to infant cry as described above. Next, multivariate regressions were run to determine the relationship between (i) testosterone and negative infant interpretations and (ii) testosterone and self-reported negative emotions while listening to infant cry. All analyses included gestational age of the infant and father's age as covariates.

We adjusted for multiple comparisons using the Holm–Bonferroni method (Holm, 1979), in which the alpha value is adjusted such that the lowest *P*-value ($I = 1$) is expected to fall below a/k, where k is the number of analyses) and the higher values to progressively less restrictive thresholds ($a/(k - I + 1)$. Therefore, for six planned analyses, we would require at least one model be significant at $P = 0.008$ (0.05/)6, one model significant at 0.01 (0.05/5), one at 0.013 (0.05/4), one at 0.017 (0.05/3) and one at 0.025 (0.05/2).

Results

First, all data were explored for outliers and normality of distribution. All variables met the criteria for normality. One subject was dropped due to neural activation in the contrast of interest (cry > white noise) being three standard deviations above the mean. Means and standard deviations of all study variables are presented in Table 1, and bivariate correlations of main study variables are shown in Table 2.

Hypothesis 1

As depicted in Table 3 and Figure 1, greater activation to infant cry than frequency-matched white noise emerged primarily in areas of the bilateral temporal lobes consisting of the auditory cortices. These areas included bilateral planum temporale, left insular cortex, R Heschl's gyrus, R STG (posterior and anterior), R planum polare and left supramarginal gyrus, as well as the right IFG. No differences were found in amygdala activation in response to infant cry *vs* white noise. No activation differences were found in response to white noise > infant cry.

Hypothesis 2

A paired samples t-test was used to test for differences in handgrip modulation during infant cry and white noise across fathers. This hypothesis was not supported. No significant differences were found in the ratio of half-strength/full-strength during infant cry *vs* white noise across fathers ($t(40) = -1.21$, $P = 2.32$). Given the lack of a main effect finding of handgrip modulation during infant cry compared to white noise, no further analyses were done testing the relationship between handgrip strength during infant cry and testosterone or psychological and neural responses to infant cry.

Hypothesis 3

This hypothesis was partially supported. Neural activation in whole-brain analyses was not associated with fathers' self-reported negative emotions or their negative trait ratings of infant cry when using whole-brain analyses. Negative interpretations of infant cry (trait rating task) predicted right amygdala percent signal change to infant cry ($B = 0.36$, $P = 0.04$; Table 4), but this effect was not significant following correction for multiple comparisons. Handgrip force was not tested given the null findings in hypothesis two.

Hypothesis 4

As hypothesized, expectant fathers with higher prenatal testosterone showed greater activation to infant cry sounds relative to white noise sounds in the right supramarginal gyrus, the left occipital cortex and the precuneus cortex (Table 5, Figure 2). No activation was found to be negatively associated with prenatal testosterone level. Prenatal testosterone level did not predict fathers' negative emotion ratings in response to infant cry

Table 2. Bivariate correlations of main study variables

Variables		1	2	3	4	5	6	7
1	Avg handgrip cry	-						
2	Avg handgrip control	0.88**	-					
3	ERQ	−0.07	−0.08	-				
4	Trait rating task	−0.09	−0.13	0.48**	-			
5	Aggregate testosterone	0.17	0.09	0.12	0.15	-		
6	Age	−0.03	0.04	0.10	0.00	−0.27	-	
7	Days pregnant	0.04	0.05	0.08	0.24	−0.32*	0.26	-

**$P < 0.01$, *$P < 0.05$, Avg = Average

Table 3. Neural activation during infant cry ($N = 34$)

Trial type	Region	x	y	z	Z-max	Voxels
Main effect Cry > control						
	L supramarginal gyrus	−46	−10	2	5.48	4673
	L planum temporale	−50	−36	14	5.12	
	L insula	−46	4	−6	4.86	
	L temporal pole	−46	14	−8	4.68	
	R planum temporale	62	−10	4	5.93	4430
	R superior Temporal gyrus, posterior	66	−14	−4	5.20	
	R Heschl's gyrus	50	−18	4	4.93	
	R planum porale	48	2	−8	4.81	
	R superior temporal gyrus, anterior	66	0	−6	4.70	
	R inferior frontal gyrus	53	29	12	2.58	

Note: x, y, and z refer to MNI coordinates; Z-max refers to the peak level of activation intensity; voxels refers to the number of voxels in each significant cluster; L and R refer to left and right hemispheres.

($B = 0.12$, $P = 0.52$) nor negative ratings of the infant during infant cry ($B = 0.22$, $P = 0.16$).

Discussion

This study sought to characterize neural, behavioral and psychological responses to infant cry sounds among expectant fathers and to examine whether their testosterone levels were associated with these responses to cry sounds. Our hypotheses were partially supported. As expected, infant cry (*vs* white noise sounds) elicited activation in regions including the superior temporal gyrus, IFG and insula, although we did not find expected differences in amygdala activation. Additionally, parts of the auditory cortices such as the planum temporale, Heschl's gyrus and supramarginal gyrus were additionally found to be more active during infant cry than a frequency-matched white noise, similarly to previous studies of first-time fathers and expectant fathers (Li *et al.*, 2018; Thijssen *et al.*, 2018). The planum temporale is situated posterior to the primary auditory cortex and has been found to be active during the processing of speech-related cues (Baars and Gage, 2010), locating sound in space (Hickok, 2009) and stimulus selection and auditory attention (Hirnstein *et al.*, 2013). The supramarginal gyrus has been implicated in phonological processing (e.g. Saur *et al.*, 2008; Church *et al.*, 2011) and in social cognition (Silani *et al.*, 2013; Singer and Klimecki, 2014). Our sample of expectant fathers appeared to recognize infant cry sounds as a meaningful speech signal over and above a frequency-matched white noise.

Additionally, areas of the brain associated with social cognition (i.e. insula, supramarginal gyrus) appear to be more active during cry than white noise. Previous research has suggested

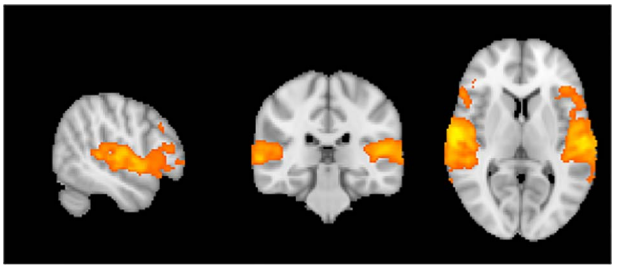

Fig. 1. Main effects for the contrast of interest infant cry > frequency-matched white noise. Revealed activation in the L supramarginal gyrus, L and R planum porale, L Insula, L temporal pole, R superior temporal gyrus, anterior and posterior, R Heschl's gyrus, R planum porale, and R IFG. Analyses cluster corrected at $z = 2.3$. ($N = 34$).

that, in contrast to biological mothers, who form a physical bond with the infant prior to birth, the paternal brain primarily comes 'online' after the birth of a child and in interacting with their newborn (Abraham *et al.*, 2014). However, the current research suggests that infant cry is nevertheless a salient stimulus for expectant fathers, even though they have not yet participated in caregiving for their own infants. Fine-tuning of these processes may occur with socialization with the infant as has been previously hypothesized (Atzil *et al.*, 2012; Abraham *et al.*, 2014; Feldman, 2015). However, the current study suggests that expectant fathers show processing of infant cry that is similar to mothers and to fathers whose child is already born. Future studies would benefit from including expectant fathers at different stages of pregnancy or age-matched non-fathers to understand whether

Table 4. Summary of multiple regression analysis for variables predicting left and right amygdala activation to infant cry compared to white noise

	Left amygdala						Right amygdala					
	t	P	β	F	df	P	t	P	β	F	df	P
Model 1				1.17	3,29	0.34				1.96	3,29	0.15
Trait rating task	1.7	0.33	0.11				2.5	**0.02** *	0.46			
Age	−0.15	−0.03	0.88				0.18	0.85	0.03			
Days pregnant	−1.27	0.21	−0.26				−0.15	0.26	−0.23			
R^2			0.11						0.17			
Model 2				1.14	3, 29	0.35				0.70	3, 29	0.56
Emotion reaction	1.65	0.11	0.29				1.4	0.16	0.26			
Age	−0.45	0.65	−0.08				−0.23	0.82	−0.04			
Days pregnant	−0.76	0.45	−0.14				−0.22	0.83	−0.04			
R^2			0.11						−0.03			
Model 3				0.13	3,30	0.51				1.12	3, 30	0.36
Prenatal T	1.26	0.22	0.25				1.81	0.08	0.35			
Age	0.04	0.97	0.01				0.45	0.65	0.09			
Days pregnant	−0.38	0.70	−0.07				0.20	0.84	0.04			
R^2			0.07						0.31			

*$P < 0.05$. Bold = significant values.

Table 5. Associations between neural activation on task and prenatal testosterone (N = 32)

Trial type	Region	x	y	z	Z-max	Voxels
Positive associations with testosterone						
Cry > control						
	R supramarginal gyrus	37	−44	60	4.24	184
	L occipital cortex	−34	−68	52	4.18	262
	Precuneus cortex	−10	−68	62	3.85	

Note: x, y and z refer to MNI coordinates; Z-max refers to the peak level of activation intensity; voxels refers to the number of voxels in each significant cluster; L and R refer to left and right hemispheres.

similar brain responses emerge in non-parents and if not, when and how these brain responses come 'online' during pregnancy.

Although we did not find a main effect for amygdala activation in response to infant cry *vs* white noise, we did find that fathers' negative views of infant cry predicted greater right amygdala activation during infant cry compared to white noise. This finding contradicts a previous study that found no relationship between amygdala activation and mothers' reported irritation during infant cry (Riem *et al.*, 2012), suggesting that this finding may be specific to expectant fathers. However, this result should be interpreted with caution given that it did not reach the level of significance after controlling for multiple comparisons. Amygdala activation has been found to be greater during infant cry compared to other forms of infant stimuli (such as laughter), and activation in these areas has been purported to underlie parental vigilance to infant distress cues (Abraham *et al.*, 2014). Amygdala activation may also represent the hub of the emotion-processing sub-network of the parenting brain (Feldman, 2015; Abraham and Feldman, 2018).

Counter to hypotheses, no difference in handgrip modulation was found during infant cry compared to frequency-matched white noise. Several reasons may explain these null results. Firstly, although handgrip has been used to reflect potential aggression in response to infant cry in previous studies (Crouch *et al.*, 2008), these studies did not include a control sound comparison. Similar null results were found in another population of expectant fathers (Alyousefi-Van Dijk *et al.*, 2019) when comparing handgrip during infant cry and a frequency-matched white noise. These results together suggest that handgrip modulation may not be a specific response to infant cry per se but may reflect hyperarousal to aversive stimuli in general. Our null results may also be due to limitations of the handgrip task itself or an underpowered sample size. It was challenging for participants to master the half-strength grip procedure, and many subjects became frustrated during the training. It may be that this task is not reliable enough across participants to indicate a sensitive response to infant cry.

The relationship between psychological and neural response to infant cry was additionally only partially supported in the current investigation, unlike previous studies which found a relationship between neural activation in auditory cortices and greater irritation to infant cry in new fathers (Li *et al.*, 2018). However, these results are in line with a previous investigation of mothers which failed to find a relationship between reported aversiveness of infant cry and neural activation to the same sound (Riem *et al.*, 2012). These null results may be due to a small sample size and an underpowered whole-brain analysis. However, the current sample size is in line with the previous investigations (Riem *et al.*, 2012; Li *et al.*, 2018). Additionally, this relationship may be stronger in fathers who could be at risk for aggressive parenting or abuse. The current investigation sought to characterize the neural and psychological response to infant cry in a community sample of expectant fathers and thus may not capture the responses indicative of abusive parenting risk.

Higher prenatal testosterone predicted greater activation in right supramarginal gyrus, left occipital cortex and the precuneus cortex. As stated above, previous studies have found the supramarginal gyrus to be implicated in social cognition

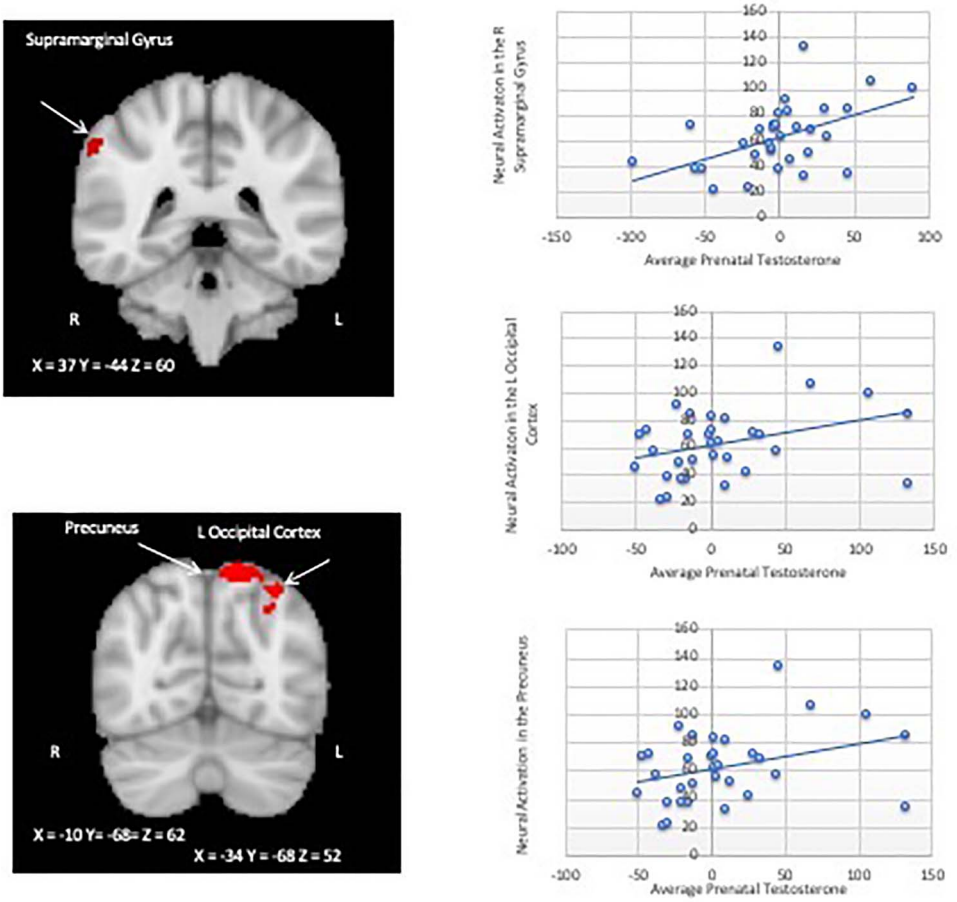

Fig. 2. Whole-brain associations with neural activation during infant cry > white noise and prenatal testosterone level as regressor, peak cluster results. Greater activation in the right supramarginal gyrus, precuneus and L occipital cortex was found during infant cry compared to frequency-matched white noise in expectant fathers with higher prenatal testosterone level. Corresponding scatterplots show signal change in these areas associated with testosterone level. All analyses cluster-corrected at $z = 2.3$, $P < .05$. R = right; L = left ($N = 32$).

(Silani *et al.*, 2013; Singer and Klimecki, 2014) and the precuneus cortex to be associated with arousal and reward learning (Swain, 2011). Previous studies of first-time fathers and baseline T found no neural activation differences in infant cry *vs* white noise in conjunction with T level (Li *et al.*, 2018). However, T reactivity to infant stimuli has been found to be associated with greater neural activation in the left caudate to infant cry while listening to infant cry and watching infant video stimuli (Kuo *et al.*, 2012). Given that this is the first investigation to look at neural activation to infant cry in expectant fathers and baseline prenatal T levels, this finding may be specific to the prenatal period. Additionally, greater activation to infant cry in association with higher T level may indicate a hyperreactivity to infant cry in line with previous investigations that have found a positive relationship between neural activation and greater reports of irritation to infant cry in new fathers (Li *et al.*, 2018). However, the current investigation did not measure parenting behaviors post-partum in these fathers with higher T. Future studies can investigate whether fathers' prenatal responses to cry sounds predict their actual parenting behaviors following the birth of their child and how this relates to testosterone level across pregnancy.

The current study had a number of limitations. Our sample size was small (34 fathers), albeit larger than the samples used in most published studies of the parenting brain. Moreover, we used a multimodal approach, incorporating behavioral (handgrip), hormonal (testosterone) and self-report data as well as MRI data. Another limitation is that because our sample consisted of expectant fathers, we were not able to present own infant sounds and instead played unfamiliar cry sounds. However, this limitation is balanced by the advantage that the stimuli was standardized across participants and has been used in previous studies even with participants who were already parents. Additionally, testosterone levels and neuroimaging responses were collected on different days and therefore may not fully map onto each other. Finally, these data are cross-sectional, focusing only on expectant fathers. Future studies can extend this work by focusing on prenatal responses to cry as a predictor of later parenting behavior. Given the exploratory nature of this study and the novel population included, future research should endeavor for an increased sample size to replicate and clarify these results.

Despite its important limitations, this study is one of the first to investigate responses to infant cry in expectant fathers across multiple modalities. Our sample was ethnically diverse and contributed hormonal, behavioral, neural and self-report data. Our findings suggest that expectant fathers process infant cry as a salient and meaningful speech sound that may require empathic responding, even before the child is born. Additionally, it appears that testosterone may moderate this effect, with expectant fathers who were higher in testosterone

also showing stronger neural responses to infant cry. Given the importance of fathers to healthy child development, this work contributes to our understanding of the fathering brain and can ultimately improve the detection of fathers at risk and inform the development of interventions that target expectant fathers.

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Conflict of interest

The authors declare no competing interests.

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