Anxious parents show higher physiological synchrony with their infants

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Abstract

Background. Interpersonal processes influence our physiological states and associated affect. Physiological arousal dysregulation, a core feature of anxiety disorders, has been identified in children of parents with elevated anxiety. However, little is understood about how parent-infant interpersonal regulatory processes differ when the dyad includes a more anxious parent.

Methods. We investigated moment-to-moment fluctuations in arousal within parent-infant dyads using miniaturised microphones and autonomic monitors. We continually recorded arousal and vocalisations in infants and parents in naturalistic home settings across day-long data segments.

Results. Our results indicated that physiological synchrony across the day was stronger in dyads including more rather than less anxious mothers. Across the whole recording epoch, less anxious mothers showed responsivity that was limited to ‘peak’ moments in their child’s arousal. In contrast, more anxious mothers showed greater reactivity to small-scale fluctuations. Less anxious mothers also showed behaviours akin to ‘stress buffering’ – downregulating their arousal when the overall arousal level of the dyad was high. These behaviours were absent in more anxious mothers.

Conclusion. Our findings have implications for understanding the differential processes of physiological co-regulation in partnerships where a partner is anxious, and for the use of this understanding in informing intervention strategies for dyads needing support for elevated levels of anxiety.

Keywords: anxiety, perinatal mental health, physiology, synchrony, parent, infant, stress regulation
Introduction

Research has shown continuity of lifetime anxiety disorders from parents to children: multiple anxiety disorders pose a significant risk of anxiety in offspring (Lawrence et al., 2019). However, while anxiety disorders aggregate in families, the reasons for this are still not yet understood (Murray et al., 2009). Genes associated with an underlying liability towards current anxiety symptoms across the population are largely shared with those predisposing individuals to professionally-diagnosed lifetime anxiety disorder (Purves et al., 2019), yet evidence acknowledges the key role of environmental influences in the development of anxiety (Eley et al., 2015). Early childhood has been found to be a crucial period for identifying environmental risk factors for anxiety disorder (Möller et al., 2016), including the potential for early identification of high risk individuals, and for preventative, early interventions. The present study examines, therefore, how anxious symptoms in parents relate to affect co-regulation in parent-infant dyads.

In both anxious and non-anxious families, there is considerable evidence that parents play a positive role in regulating children’s physiological, behavioural and affective states (Bridgett et al., 2015; Reddy et al., 1997). Behavioural studies have, for example, identified sensitive parenting behaviours that mediate the relationship between household chaos and infant self-regulatory skills (Vernon-Feagans et al., 2016), and parental encouragement mediates the relationship between parent anxiety and anxiety symptoms in early childhood (Murray et al., 2008, 2009). Physiological studies examining how autonomic arousal co-fluctuates in infant-parent dyads have traditionally concentrated on physiological synchrony, referring to a range of temporally interdependent or associated activities in the physiological processes of two partners (Davis et al., 2018; McFarland et al., 2020). Previous research has suggested that the benefits of synchrony are bidirectional (Feldman, 2007): the parent, by adapting to the child, helps by responding contingently to the
child’s needs (Feldman, 2009); the child, by adapting to the parent, gains both self-control, and self-awareness (Feldman, Greenbaum, & Yirmiya, 1999). Previous research has identified synchronous patterns of change in physiological arousal in the lab following the administration of experimental stressors (Ham & Tronick, 2009). Recent research that recorded naturalistic arousal co-fluctuations in infant-parent dyads found that synchronous patterns of co-fluctuating arousal were not observed across all arousal states: rather, that short-term increases in parent-child synchrony were triggered in response to ‘peak’ instances of physiological arousal in the infant, but that synchrony at other times was not observed (Wass et al., 2019).

There is also substantive evidence that anxious parenting can associate with the dysregulation of behavioural and physiological states in children (Nikolić et al., 2016). Behavioural studies examining tabletop play between anxious parents and their infants found evidence for an ‘overloaded, highly stimulating’ behavioural profile in anxious mothers (Feldman, 2007), along with higher levels of behavioural synchrony (Beebe et al., 2011; Granat et al., 2017). Anxiety in these studies was measured via self-report questionnaire. Experimental investigations have also shown overactive regulatory responses from infants of anxious mothers, particularly following the onset of positive social stimuli (Granat et al., 2017). Lab-based physiological studies have found evidence for ‘stress contagion’, whereby increases in autonomic activity in the mother are reflected in increases in the infant following emotionally-valenced experimental tasks (Waters et al., 2014, 2017). However, naturalistic investigations of physiological synchrony between infants and parents with anxiety are minimal.

Overall, studies of maternal anxiety and physiological dysregulation in early childhood remain scant. Arousal dysregulation (often defined as increased autonomic changes in response to an experimentally administered challenge, along with longer recovery times (e.g. Beauchaine &
Thayer, 2015) is a core feature of anxiety in adulthood (Ottaviani et al., 2016; Thayer et al., 1996) and middle childhood (Dieleman et al., 2015; Koszycki et al., 2019), but the majority of research on this topic focuses on children aged 6 or over (Siess et al., 2014). In addition, these findings examine change relative to a stressor, with a discrete and experimenter-defined start and end period, administered during short periods (~<10 minutes) of lab-based interaction. No previous research has examined whether spontaneous fluctuations in a child and parent’s biological and behavioural systems associate with one another in naturalistic, day-to-day settings, assessing how these relationships differ between more or less anxious parents. Additionally, while emotion dysregulation is also characteristic of anxiety disorders (Amstadter, 2008; Hofmann et al., 2012), there has been little study into the relationship between affect states and physiological dysregulation in mother-infant pairs where the mother has anxiety. One issue with measuring hyperarousal alone is that its valence cannot be determined; to resolve this, vocal signals of positive or negative affect may be used to identify valence (as in previous work showing that extremes of valence are more likely at elevated levels of arousal; see Wass et al., 2019). To our knowledge, no previous research has disaggregated infant recovery from an instance of physiological hyperarousal with positive or negative valence, and examined whether the relationship between infant recovery and maternal reactivity to positive or negative hyperarousal events varies by maternal anxiety.

To address this, we developed new techniques, including miniaturised microphones, video cameras, electro-cardiograms, and actigraphs that could be worn concurrently by infants and parents for a day at a time at home (Maitha et al., 2020; Wass, Smith, Clackson, et al., 2019; Wass, Smith, Daubney, et al., 2019). We recorded both partners’ autonomic fluctuations during the day, by measuring heart rate (RR intervals, where R is the peak of the QRS complex of the ECG wave),
heart rate variability, and movement (via actigraphy). According to previous research, elevated heart rate, decreased heart rate variability and increased movement are associated with increased physiological stress, i.e. a higher ratio of sympathetic to parasympathetic nervous system activity (Cacioppo et al., 2007). We also recorded the auditory environment, and coded the vocalisations spoken by the infant, and those directed to the infant by the parent.

The goal of the current study was to examine associations between the physiological profiles for infant-parent dyads with higher or lower measures of maternal anxiety. In the analyses of two partners’ time series data, a well-established distinction has been drawn between ‘concurrent’ synchrony (‘when A is high, B is high’) and ‘sequential’ synchrony (‘changes in A forward-predict changes in B’ – see Wass et al., 2020). Given previous evidence, we asked a set of four interlinked questions from around four hours per dyad of continuously measured parent and child arousal data:

First (Hypothesis 1), we examined the degree of concurrent and sequential infant-parent arousal synchrony across the full time-series of home-based data from each dyadic pair. We predicted that both forms of synchrony would be greater in dyads with more anxious parents.

Second, across the next three analyses we examined how overall levels of dyadic synchrony relate to structured variation in the degree of synchrony across the time-series. In hypothesis (2), we asked how sequential synchrony varies in relation to the current levels of arousal in both dyadic partners, considered at the same time – and we examined how this differs by parental anxiety level. We predicted that arousal changes in each partner considered independently would be influenced by the overall level of arousal of the dyad, and that this relationship would differ contingent on parental anxiety.
Third, since previous research (Wass et al., 2019) has shown that synchronous responses may be constrained to highly stressful events, we went on to focus analysis on moments when the infant showed a peak in their arousal (Hypothesis 3). We predicted that more anxious parents would show greater event-related physiological hyper-arousal.

Finally, peak arousal events in the infant could be positive or negative in affect. In hypothesis (4) we predicted that parents’ event-related hyperarousal would associate with infants’ hyperarousal across different emotionally valenced events.
Method

Experimental participant details

The project was approved by the Research Ethics Committee at the University of East London. Participants were recruited from the London, Essex, Hertfordshire and Cambridge regions of the UK. In total, 91 infant-parent dyads were recruited to participate in the study, of whom usable autonomic data were recorded from 82. Of these, usable paired autonomic data (from both parent and child) were obtained from 74 participants. 68 of these participants also completed the full anxiety screening questionnaire. A consistent outlier-detection strategy was applied equally for all analyses, by excluding outliers that were >2 inter-quartile range (IQR) from the mean, to avoid violating the assumptions of the statistical tests being conducted. Outliers were only found for the analyses presented under Hypothesis 1 and 2, reported below in the Results. Further details, including exclusion criteria, and detailed demographic details on the sample, are given in Table 1 and SM section 1.1. Of note, we excluded families in which the primary day-time care was performed by the male parent, because the numbers were insufficient to provide an adequately gender-matched sample. All participating parents were, therefore, female. Participants received £30 in Love2Shop gift vouchers as a token of gratitude for participation, split over two visits.

Parent screening

To screen parents for maternal anxiety, participants filled out the Generalized Anxiety Disorder 7-item screener (GAD-7), which assesses anxiety symptoms over the past two weeks (Spitzer et al., 2006). Responses were given on a 4-point scale ranging from 0 (not at all) to 3 (nearly every day). Validity for this questionnaire has been provided by studies with clinical and non-clinical populations, with scores above 6 representing moderate anxiety (Löwe et al., 2008). The internal consistency of the scale was $\alpha = .89$. 
The mean \((std)\) \((range)\) of scores obtained on the GAD-7 was 3.4 \((3.9)\) \((0-17)\). A median split was performed to differentiate between high and low anxiety groups. Dichotomization of this variable was necessary due to our statistical analysis plan (in particular, our use of time series analyses), though additional analyses based on a quintile split were used to explore the consistency of associations (see SM 2.1). The mean \((std)\) \((range)\) GAD-7 score was 0.76 \((0.85)\) \((0-2)\) for the low anxiety group and 6.16 \((3.96)\) \((3-17)\) for the high anxiety group, indicating mild to moderate anxiety.

**Experimental method details**

Participating parents were invited to select a day during which they would be spending the entire day with their child but which was otherwise, as far as possible, typical for them and their child. The researcher visited the participants’ homes in the morning \((c. 7.30 - 10am)\) to fit the equipment, and returned later \((c. 4 - 7pm)\) to pick it up. The mean \((std)\) recording time per day was 7.3 \((1.4)\) hours.

The equipment consisted of two wearable layers, for both infant and parent (see Figure 1). For the infant, a specially designed baby-grow was worn next to the skin, which contained a built-in Electrocardiogram (ECG) recording device \((recording at 250Hz)\), accelerometer \((30Hz)\), Global Positioning System (GPS) \((1Hz)\), and microphone \((11.6kHz)\). A T-shirt, worn on top of the device, contained a pocket to hold the microphone and a miniature video camera \((a commercially available Narrative Clip 2 camera)\). For the parent, a specially designed chest strap was also worn next to the skin, containing the same equipment. A cardigan, worn as a top layer, contained the microphone and video camera. The clothes were comfortable when worn and, other than a request to keep the equipment dry, participants were encouraged to behave exactly as they would do on a
normal day. To ensure good quality recordings, the ECG device was attached using standard Ag-
Cl electrodes, placed in a modified lead II position.

[Figure 1]

Quantification and statistical analysis

Autonomic data parsing and calculation of the autonomic composite measure. Further
details on the parsing of the heart rate, heart rate variability, and actigraphy are given in the SM
(section 1.2). To ensure the accuracy of these recording devices, they were cross-validated by
recording heart rate and heart rate variability using both the new devices at home and established
recording devices (a Biopac MP150 amp recording at 2000Hz) in lab settings. High reliability was
observed both for heart rate (rho=.57, p<.001) and heart rate variability (rho=.70, p=.01). In the
SM (section 1.3) we also present further details on our motivation for collapsing these three
measures into a single composite measure of autonomic arousal.

Affect coding. The microphone recorded a 5-second snapshot of the auditory environment
every 60 seconds. Post hoc, coders identified samples in which the infant was vocalising, and
coded them for vocal affect on a scale from 1 (fussy and difficult) to 9 (happy and engaged). In
order to assess inter-rater reliability, 24% of the sample was double coded; Cohen’s kappa was
0.60, which is considered acceptable (McHugh, 2012). All coders were blind to intended analyses.
Negative affect vocalisations were defined as all vocalisations coded as 4 or less; positive affect
vocalisations included all vocalisations coded on 6 or more; neutral affect vocalisations include
vocalisations coded 5.

Home/Awake coding. Our analyses only examine segments of the data in which the dyad
was at home, and the infant was awake. This is because our preliminary analyses suggested that
infants tended to be strapped in to either a buggy or car seat for much of the time that they were outdoors, which strongly influenced their autonomic data. Further details for how these home/awake segments were identified are given in the SM (section 1.4). Following these exclusions, the mean \( (std) \) total amount of data available per dyad was 3.7 \( (1.7) \) hours, corresponding to 221.5 \( (102.4) \) 60-second epochs per dyad.

**Cross-correlation analyses.** To test hypothesis 1, we used cross-correlation to examine relations between concurrently measured epochs of parent and infant arousal. Infant and adult arousal data were synchronised, 60-second epoched and linear de-trended. Spearman’s rank order correlations were conducted across all pairs of time-locked (i.e., simultaneously occurring) epochs for infant and parent and plotted as time “0” \( (t = 0) \). Correlations between non-simultaneous pairs were then computed and plotted against time lag and direction on the x axis (adult’s arousal forward-predicting infant arousal on the positive axis, infant arousal forward-predicting adult arousal on the negative). Figures present data for a selected epoch of 600 seconds before to 600 seconds after an event to fully contextualise profiles of change around the focal point (see Thorson, West, & Mendes, 2018). Permutation-based temporal clustering analyses were applied to correct for multiple comparisons across time bins (see below, and SM section 1.6 for more details).

**Vector plots.** To test hypothesis 2, we computed vector plots. To do this, all infant and adult arousal data were downsampled into 60-second epochs and collated into six equally sized bins, individually for each participant (infant and adult). Each epoch was then classified according to what bin it fell into for both infant arousal and parent arousal. This is represented as a two-dimensional matrix – so all epochs that were bin 3 for infant arousal and bin 4 for adult arousal are drawn at location \([x \ -3, \ y \ -4]\). The size of each dot within the matrix indicates what proportion of the total available samples was located within each bin. For each bin, we then
calculated the average change from all epochs in that bin, to the epochs immediately following. This change score is drawn on the vector plot as a red line. Thus, for the point located at [6,6] on the vector plot, which represents all epochs that were classified as in bin 6 for both infant arousal and parent arousal, the vector extends -0.8 on the x-axis (representing change in infant arousal), and -1 on the y-axis (representing change in adult arousal). This indicates that, across all epochs starting from [6,6], the average change to the next epoch was a reduction of 0.8 bins in infant arousal, and 1 bin in adult arousal.

These plots therefore allow us to examine how the parent’s present arousal level interacts with the child’s present arousal level in predicting the change in parent arousal – i.e., how the change in one partner’s arousal is influenced by both partners’ arousal, considered in combination. To quantify this, we compared the change in adult arousal between the bottom right (high infant-low adult arousal) and bottom left (low infant-low adult arousal) quadrants of the Vector plot; and between the top right (high infant-high adult arousal) and top left (low infant-high adult arousal) quadrants of the Vector plot. The observed results are compared to a chance value of 0 using a t-test.

**Permutation-based temporal clustering analyses.** To estimate the significance of time-series relationships, a permutation-based temporal clustering approach was used for the analyses presented under Hypotheses 1, 3 and 4. This procedure, which is adapted from neuroimaging (Maris & Oostenveld, 2007; Maris, 2012), allows us to estimate the probability of temporally contiguous relationships being observed in our results, a fact that standard approaches to correcting for multiple comparisons fail to account for (Maris and Oostenveld, 2007; see also Oakes et al., 2013). See further details in SM section 1.5.
Results

Raw data and descriptives

Prior to testing our four main hypotheses, we first present raw data and descriptive analyses. Figure 2 shows a raw data sample of the home data, and Table 1 shows demographic data for the sample, subdivided by low/high GAD-7 scores. Independent samples t-tests were conducted for all demographic variables (i.e. with the exception of ethnicity) to assess whether significant group differences were observed. No significant differences were identified (all ps>.15).

As a preliminary analysis, we examined how the low/high GAD-7 groups differed on mean arousal levels across the day. This analysis was based on the raw autonomic data included in the arousal composite, prior to the calculation of z scores on a per-participant basis for the composite measure. When considering just samples in which the dyad was at home, and the infant was awake, t-tests indicated no differences between the lower/higher anxiety groups on any of the heart rate variables included in the z-scored composite, namely mean waking heart rate, sleeping heart rate, waking or sleeping heart rate variability, for either infants or parents (all ps>.27). Hence, arousal levels did not differ significantly between the groups. Waking movement levels were, however, significantly lower in the high GAD-7 group $t(69)=2.17, p=.03$.

Hypothesis 1 - concurrent and sequential infant-parent synchrony in physiological arousal is greater in dyads with more anxious parents

To test this hypothesis, we examined the cross-correlation between infant and parental arousal. Prior to conducting the t-test group comparisons described below, two outliers (one from each group) were excluded using the >2 inter-quartile range (IQR) criterion.
In previous research we used an identical analysis to show that, across all parents, no significant temporal co-fluctuation in infant and parental autonomic arousal levels is observed (Wass et al., 2019). When results are subdivided by parental anxiety, however, a significant zero-lagged cross-correlation between infant and parent arousal is observed in the anxious group (t-test vs chance value of 0 (t(32)=4.2, p<.001) but not the non-anxious group (t(32)=1.03, p=.32 (Figure 3a). Group comparisons indicated higher zero-lagged cross-correlations in Group 1 vs Group 2: t(64)=2.16, p=.035. In sum, when considering all home-awake segments of the day, there is significant co-fluctuation in autonomic arousal between parent and child arousal in the high GAD-7 but not the low GAD-7 group.

Further details and interpretation of the cross-correlation function are given in the SM section 2.1. In this section, we also provide a further analysis subdividing our groups using a quintile split by GAD-7 score (see Figure S2). This shows the relationship between arousal cross-correlation and GAD-7 is distributed uniformly across the sample, and highest in participants with the most elevated levels of anxiety.

Hypothesis 2 - arousal changes in each partner will be influenced by the overall arousal level of the dyad; this relationship will differ contingent on parental anxiety

Hypothesis 1 examined differences in arousal synchrony across all data collected while the dyad was at home and the infant was awake. In addition, we also wished to examine how inter-dyadic influences in arousal would vary contingent on the arousal level of parent and child, considered separately. To examine this, we calculated a vector plot (see Methods).

The parent-infant arousal change score is drawn on the vector plot as a red line. For example, for the point located at [1,1] on the vector plot (Figure 4a), the vector extends +0.3 on
the x-axis (representing change in infant arousal), and +0.7 on the y-axis (representing change in adult arousal). Hence, across all epochs starting from [1,1], the average change to the next epoch was a gain of +0.3 bins in infant arousal, and +0.7 bins in adult arousal (see Figure 4a, 4b). Across all data, the vectors tend to point towards the centre of the plot. This indicates regression to the mean: in an epoch where infants’ and parents’ arousal starts low, an increase is expected to the next epoch; whereas for an epoch that starts high, a decrease is expected. The centre point of the vectors appears to be around bin 4 (out of 6), consistent with the lightly positively skewed distribution observed across all data (see Wass et al., 2019).

In order to examine how the change in one partner’s arousal is influenced by both partners’ arousal considered in combination we can examine, for example, the bottom rows of each vector plot (Fig 4a-b), which show instances in which the adult’s arousal is low. The bottom left quadrant (shaded yellow on Figure 4c) shows instances in which both parent and infant arousal is low; the bottom right quadrant (shaded red) shows instances in which the parent arousal is low but infant arousal is high. To estimate whether, in both groups, the change (increase) in adult arousal is greater where the infant’ arousal is high than when it is low, we calculated the change in adult arousal between the bottom right and bottom left quadrants of the vector plot (Fig. 4c), and compared the observed results to a chance value of 0 using a t-test. Results from four participants were excluded (three low/one high) were excluded using the +/- 2IQR rule. For both the low (t(30)=2.03, p=.05) and high (t(32)=2.39, p=.02) GAD-7 groups, marked differences from zero were observed. Hence, when adults’ arousal is low and infants’ arousal is high, then adults show upregulation in their arousal in response – a feature which is present in both the low and high GAD-7 groups.
The top rows of the vector plot (Fig 4c-4d) show instances in which the adult’s arousal is high. In the non-anxious group, it appears that the negative vertical displacement of the lines is greater in the top right quadrant (shaded green on Figure 4c), compared to the top left quadrant (shaded brown). If true, this would indicate that, when the adult’s arousal starts high, their arousal decreases more in instances where the infant’s arousal is high, than when it is low. To estimate this, we calculated the change between quadrants, and compared the observed results to a chance value of 0 using a t-test. Results from three participants were excluded (one low/two high) using the +/- 2IQR rule. For the lower anxiety (t(32)=2.16, p=.04) but not the higher anxiety (t(31)=0.75, p=.46) groups, a significant difference was observed. An independent samples t-test also identified a significant difference between groups on this measure t(63)=2.05, p=.045. Hence, when the overall arousal level of the dyad is high, then adults show downregulation in their arousal in response – but that this feature is only present in the low GAD-7 group.

Hypothesis 3 - more anxious parents will show greater event-related physiological hyperarousal

Hypothesis 1 examines parent-infant synchrony, i.e. the continuous association between parent and infant arousal across all data. In addition, and motivated by previous findings (Wass et al., 2019) we also examined adult reactivity to ‘peak’ arousal events from the infant. Figure 5a shows a schematic illustrating this analysis. First, adult’s arousal data were z-scored, participant by participant. Next, instances where the infant’s arousal crossed a centile threshold (e.g. exceeded the 97th centile of samples for that infant in that day) were identified. Then, for each instance, the average change in adult arousal from 600 seconds before to 600 seconds after the infant peak arousal moment was excerpted (see Figure 5b). This allows us to examine how the adult’s arousal changes on average around the top 3% most elevated arousal moments for that infant in that day.
Then, we repeated the analysis using different values for the centile threshold (Figure 5b), to examine instances where the infant’s arousal exceeded the 95th centile of samples for that infant in that day, the 90th centile, and so on, down to the 75th centile.

We were interested to examine whether a significant peak in parent arousal was observed relative to the peak arousal moment in the infant, and whether peaks in parent arousal were only observed for the most extreme instances of elevated infant arousal (i.e., the top 3% of samples for that infant in that day), or whether they were also observed for less extreme, yet still relatively high, arousal instances (i.e., the top 25% of sample for that infant that day). To quantify whether a significant peak in parent arousal was observed relative to the peak arousal moment in the infant, we performed a permutation-based clustering analysis (see SM section 1.6, Method 1). Instances where a significant peak was observed are drawn as coloured datapoints on Fig 5c (blue/red for high/low GAD-7 groups); instances where no significant peak was observed are drawn as black datapoints. It can be seen that, after correction for multiple comparisons, the low GAD-7 group only show peaks in parent arousal relative to the 3% and 5% most extreme instances of elevated infant arousal. In contrast, the high GAD-7 group show significant peaks in parent arousal relative to the 25%, 15%, 10%, 5% and 3% most elevated instances. Overall, these results show that both groups showed maternal reactivity to extremes of infant arousal, but that high GAD-7 parents also showed greater autonomic reactivity to less extreme arousal fluctuations in the infant.

[Figure 5]

Hypothesis 4 – parents’ event-related hyperarousal associates with infants’ hyperarousal across different emotionally valenced events
Hypothesis 3 examines how adults react to naturally occurring ‘peak’ moments in infant arousal during the day. However, high arousal levels can be positive or negative, and differently valenced infant arousal may make a difference to parent responsivity. To examine this, we also studied hyperarousal relative to vocalisations, which signal whether infants are experiencing positive or negative emotional valence. We examined how parents’ event-related hyperarousal associates with infants’ hyperarousal across different emotionally valenced events.

First, we identified all infant vocalisations that occurred during the day; for each vocalisation, we examined the rate of change of infant physiological arousal relative to these vocalisations (Figure 6a-6c). The significance of group differences was calculated by first conducting t-tests separately for each individual time bin, and then correcting for multiple comparisons using a permutation-based clustering analysis (see SM section 1.6, Method 2). As expected, all vocalisations showed a significant peak in infant autonomic arousal at time 0 – i.e. the time of the infant vocalisation (all permutation-based clustering ps<.001). The infants with high anxious mothers showed significantly higher infant physiological arousal at the time of the negative affect vocalisation, along with significantly higher infant arousal during the period 8-12 minutes after the vocalisation, indicating slower recovery (Fig 6a, p=.023). A similar pattern was evident following positive affect vocalisations (Figure 6b, p<.001), but not following neutral affect vocalisations. These differences were not attributable to differences in the frequency of vocalisations as these did not differ significantly between groups (z=.31/.50/.97, p=.75/.30/.33 for negative/positive/neutral affect vocalisations respectively).

[Figure 6]

We also wished to assess how infant recovery following a positive or negative vocalisation related to the differences in parental reactivity to moments of peak infant arousal examined in
hypothesis 3, above. To do this, we measured the degree to which maternal autonomic reactivity is specific to ‘peak’ infant arousal moments, using the following method. For each participant, the maternal arousal response to >97th centile infant arousal moments was calculated (see Figure 5b). This was done by averaging the z-scored maternal arousal values from 3 minutes before and after the peak infant arousal moment (corresponding to the peaks visible on Figure 5b; as seen in Figure 5, analyses were also repeated using other time windows with similar results). For each participant, the maternal arousal response to >75th centile arousal moments was also calculated (see Figure 5b). The degree to which maternal autonomic reactivity is specific to ‘peak’ infant arousal moments was calculated by subtracting the >97th centile arousal responses from the >75th centile responses, so that a larger value indicates that maternal autonomic reactivity is more specific to ‘peak’ infant arousal moments.

Infant recovery was assessed by calculating the average infant arousal during the period from 1200 seconds before and after the positive and negative affect vocalisations (corresponding to the time periods shown in Figure 6), and subtracting the average arousal during the period after the vocalisation from the average arousal during the period before. In order to assess how infant recovery related to parental reactivity, we calculated the bivariate correlation between the two measures. Infant recovery following negative affect related to more selective parental reactivity (i.e. a bigger difference between >97th centile and >75th centile arousal responses) $\rho=-.33$ $p=.045$. This finding was observed consistently in the lower ($\rho=-.31$) and higher ($\rho=-.50$) parental anxiety groups. No relationship was observed between the same variable and infant recovery following positive affect ($\rho=-.07$). These results show that more selective parental autonomic reactivity is associated with faster infant recovery following naturally occurring peaks of negative affect – a finding which is observed independently in both the low and high GAD-7 groups.
Discussion

The present study aimed to examine how anxious symptoms in parents relate to arousal co-regulation in parent-infant dyads. Primarily, we investigated whether concurrent and sequential synchrony in physiological arousal would be greater in dyads with more anxious parents (Hypothesis 1). We also examined how inter-dyadic influences in arousal vary contingent on the starting arousal level of parent and child, considered separately (Hypothesis 2). In addition, we examine patterns of event-related change (sequential synchrony). We examined whether more anxious parents show greater event-related changes in their own physiological arousal, relative to ‘peak’ moment of arousal in the child (Hypothesis 3). And we examined whether parents’ event-related hyperarousal associates with infants’ hyperarousal across different emotionally valenced events (Hypothesis 4). To address these questions, we used miniaturised microphones and cameras, and wearable physiological monitors, to record vocalisations and day-long physiological fluctuations in 12-month-old infants and their parents. Participating parents completed a self-rating scale of current anxiety symptoms (the GAD-7).

Our preliminary analyses indicated that mean heart rate and heart rate variability did not differ between the more or less anxious groups for either parent or infants in home settings. This is informative, because no previous research has, to our knowledge, examined baseline (resting) physiology in an infant proband sample. We did, however find differences in how arousal levels in dyads associated with each other throughout the day. Overall, dyads in the more anxious group showed higher concurrent synchrony in physiological arousal (Hypothesis 1). Conversely, in the less anxious group, mothers’ arousal levels were less tightly coupled with infant levels (Fig 3b and SM section 2.1).
Recent research has reported correlated neural activity between socially interacting animals (Kingsbury et al., 2019; Zhang & Yartsev, 2019) consistent with previous neuroimaging findings in adults (Hari et al., 2013; Hasson et al., 2012). Our results extend this by identifying, for the first time, higher physiological synchrony in anxious parent-child dyads. Although our finding is consistent with some previous evidence on behavioral synchrony in anxious dyads (Beebe et al., 2011; Granat et al., 2017), the finding of greater physiological synchrony is novel. This finding contributes to a growing evidence base suggesting that ‘sustained intervals of synchrony may be too demanding from a resource allocation perspective’ (McFarland, Fortin, & Polka, 2020, p. 58), and that a mid-range of synchrony whereby partners are neither over- nor under-coordinated is optimal (Beebe et al., 2011; Granat et al., 2017; Jaffe et al., 2001). This is important for understanding mechanisms for direct transfer of physiological stress across parent-child dyads.

Also novel are our findings examining how parents react to small- vs large-scale arousal fluctuations in their child (Hypothesis 3). Our results showed that, for the non-anxious group, significant peaks in adult arousal were observed only relative to the top 5% and top 3% most elevated instances of infant arousal, whereas, anxious parents show peaks in arousal also relative to the top 25%, 15% and 10% most elevated instances of infant arousal. Key to this finding is that anxious parents exhibited a significant change in arousal - rather than greater arousal overall. This suggests that, whereas non-anxious parents up-regulate their own arousal only relative to ‘peak’ arousal moments in their infant, more anxious parents show greater reactivity to small-scale fluctuations in their child. Thus, non-anxious mothers were ‘there when you need me’ - showing reactivity to peak child arousal events, but not otherwise. But anxious mothers were ‘always on’ – showing reactivity to small-scale child arousal fluctuations as well. In Hypothesis 4, we found that more selective parental reactivity is associated with faster infant recovery following naturally
occurring peaks of negative affect – a finding which is observed independently in both the low and high anxiety groups. These findings support evidence for an ‘overloaded, highly stimulating’ behavioural profile in anxious mothers (Feldman, 2007), that leaves insufficient time for infants to experience neutral affect, or ‘time off’, thereby losing opportunities to practice self-regulation.

Finally, our results provide new evidence on how anxious parents’ arousal levels change depending on their own and their infant’s starting arousal level (Hypothesis 2). Our results suggested that, when adults’ arousal is low and infants’ arousal is high, then adults tend to upregulate their arousal in response – a feature which is present in both the low and high anxiety groups. But, when the overall arousal level of the dyad is high, then adults tend to downregulate their arousal in response – a feature which is only present in the lower anxiety group. This latter feature potentially indicates behaviours akin to ‘stress buffering’ (Hennessy et al., 2009); this behaviour was absent among more anxious mothers. Our findings suggest that the mechanism by which affective and arousal states are transmitted from one partner to another does not operate consistently across more anxious and less anxious dyads, and may therefore be a fruitful target for further research.

Our research is limited by several factors. Firstly, our sample was sourced from the community. Subgroup analyses (see SM section 2.1, Figure S2) suggested that the relationship between arousal cross-correlation and GAD-7 was distributed uniformly across the sample, and highest in participants with most severe anxiety, although the elevated levels of anxiety found in clinical samples were relatively under-represented in our sample. Of note, there is genetic evidence that total GAD-7 scores have the same genetic underpinnings as professionally diagnosed anxiety disorders (Purves et al., 2019). Though trait scores of anxiety may be more pertinent to the general population than clinical diagnosis and have broader relevance in terms of effects, further research
with a clinical sample would be needed to investigate the effects of moderately severe and severe levels of anxiety in mothers.

A second limitation of our study is that we investigated biobehavioural relations between mother-infant dyads, and not father-infant dyads; research has suggested that gender differences in parents are relevant for childhood anxiety disorders, and should be a focus in the future (Majdandžić et al., 2014; Möller et al., 2015). A third limitation is that, though we requested participants select a typical day for the home recording session, we had no way of confirming the typicality of the day chosen; as such, there was no way to know if state anxiety, as well as trait anxiety, could be exerting an effect on parent or infant arousal. Finally, our research did not differentiate anxiety subtypes, for example general anxiety disorder versus panic disorder or social anxiety disorder; evidence suggests children respond differentially to parents on these bases, and therefore these subtypes should be incorporated into future research among mother-infant dyads (de Rosnay et al., 2006; Murray et al., 2007).

Our research provides new information on how the regulatory profiles of anxious mother-infant dyads are inter-dependent on one another. It also contributes to the evidence-base on the intergenerational transmission of anxiety from parent to infant, building on our understanding of how parent-child interactions differ in anxious parents during the first year of life. The research also provides evidence that even in mothers without a professional diagnosis of anxiety, there are apparent effects of maternal anxiety on physiological processes in both mother and infant. This information is helpful for developing our knowledge of the environmental mechanisms underlying the development of anxiety disorders, and provides a basis for future investigations into how an individual partner might downregulate another’s arousal levels. It may also inform future
intervention studies focused on reducing overall levels of anxiety in the dyad, whether or not the parent has a clinical diagnosis; for example, targeting interoceptive capacities in the parent.

Conflicts of Interest. None.

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ANXIETY AND PHYSIOLOGICAL SYNCHRONY

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