A dynamic systems account of how perinatal anxiety impacts caregiver-infant synchrony

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OVERVIEW OF CONTENTS

LIST OF ABBREVIATIONS

BDI	Beck Depression Inventory
CBP	Cluster-based permutation / permutation-based clustering [test]
CCF	Cross-correlation function
CI	Confidence Intervals
DASS	Depression Anxiety Stress Scales
DST	Dynamic systems theory
ECG	Electrocardiogram
EPDS	Edinburgh Postnatal Depression Scale
GAD-7	General Anxiety Disorder 7-item screening tool
HR	Heart rate
HRV	Heart rate variability
IAPT	Improving Access to Psychological Therapies, i.e., NHS talking therapies programme
Lab	Laboratory
LME	Linear mixed-effects model
Min	Minutes
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
PICO	Population, Intervention, Comparison, and Outcome
PROSPERO	International prospective register of systematic reviews
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
rho	Spearman's rank correlation coefficient
RSA	Respiratory sinus arrhythmia
STAI	Strait Trait Anxiety Inventory
SWC	Sliding window correlation
UK	United Kingdom
USA	United States of America

CHAPTER 1 – Systematic Review

Systematic review of the association between perinatal anxiety and caregiver-infant interaction: a dynamic systems perspective

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Abstract

Children's socio-emotional development is shaped by the caregiver-child relationship. In early development, typical caregiver-infant interaction is thought to foster emotion regulation. Caregiver anxiety in the perinatal period has been associated with disrupted interaction. I examined this in a systematic review and meta-analysis of the association between perinatal anxiety and caregiver-infant interaction, from a dynamic systems perspective. A systematic database search was performed, including studies with anxious caregivers and their child below 24 months of age. Nine studies (N = 845) met the inclusion criteria and were included in the review. Qualitative synthesis suggested over-responsive caregiving and longer episodes of tightly coordinated interaction among anxious caregivers and infants. Meta-analysis on a subset of studies showed that perinatal anxiety was positively associated with caregiver-infant synchrony (r = 0.16), such that higher levels of synchrony were observed in more anxious caregivers and their infants. Of note, literature was sparse and the risk of bias varied across studies, limiting insight into the relation between caregiver-infant interaction and child socio-emotional development. Results are discussed with respect to implications for clinical practice; video-based feedback interventions in the perinatal period may benefit from emphasising 'sticky' dyadic dynamics as well as body-behaviour links. Future research will benefit from more adequately powered, representative samples in longitudinal studies incorporating time series data.

A statement on language

In this review, I generally use the term 'caregiver' (rather than 'parent' or 'mother' or 'father') to promote inclusivity and acknowledge the diverse range of individuals involved in caregiving roles, beyond traditional gender norms. My use of this term also reflects a commitment to recognising and respecting all caregivers, including non-gestational and non-primary caregivers (all of whom were eligible for inclusion within the review). However, I also acknowledge that the included studies in this review predominantly focus on mothers, resulting in a relatively non-diverse sample. This limitation reflects the nature of the extant literature, which is largely centred on cisgender, heterosexual samples and mothers (Costigan & Cox, 2001; Darwin & Greenfield, 2019a, 2022a, 2022b) irrespective of my inclusive eligibility criteria. By using inclusive language, I aim to avoid reinforcing gendered assumptions and to affirm the value of all caregiving roles. At the same time, I recognise the importance of transparency and the need to address the lack of representation in the literature. My intention is not to obscure these issues but to advocate for a broader and more inclusive understanding of caregiving, particularly within developmental and perinatal research.

1. Introduction

Almost all our socio-emotional functions develop through early child-caregiver interaction (Geva & Feldman, 2008; Stern, 2018; Tronick, 2002). Of growing interest within child and adolescent psychopathology is the role of caregiver-infant interaction in the development of emotion regulation (Aquino et al., 2023; Quiñones-Camacho et al., 2020; Smith, Jones, Wass, et al., 2022); this is because difficulties with emotion regulation in infancy have been implicated transdiagnostically in later child psychopathology (Kostyrka-Allchorne et al., 2020). Emotion regulation is defined as the 'ongoing, dynamic, and adaptive modulation of internal [affective] state or behaviour, mediated by central and peripheral physiology' (Nigg, 2017, p. 361). In early development, it is understood as a dyadic, bidirectional process; a dynamic by which child is influenced by caregiver, and caregiver is influenced by child (Sameroff & Fiese, 1990; Tronick et al., 1998), sometimes referred to as 'coregulation' (Butler & Randall, 2013). Coregulation occurs through an interpersonal feedback loop where increases in child stress triggers compensatory changes in caregiver behaviour, thus correcting for changes in child stress; over time, children transition from inter-dependent regulation to self-regulation, though the change is gradual (Wass et al., 2024).

The child's early development of emotion regulation is affected by multiple, often interacting, factors related to the characteristics of the caregiver, child, family context and wider environment. For example, difficulties have been observed in children exposed to early life maltreatment (Gruhn & Compas, 2020), socio-economic disadvantage (Suveg et al., 2016), and caregiver distress in combination with temperamental vulnerability in the child (Calkins et al., 2019; Cutrona & Troutman, 1986). Children are especially susceptible to difficulties in emotion regulation in later life if their caregiver is less able to compensate for infant stress during early life interactions; this is likely to be the case in instances where caregivers have difficulties regulating their own emotional response when their infant is distressed (see, e.g., relations between child emotion regulation and dyadic interaction in the context of parental depression and substance misuse; Punamäki et al., 2021; Silk et al., 2006). Evidence has shown that caregiver depressive and borderline personality symptoms represent an important risk factor in this regard, predicting child socio-emotional outcomes directly and indirectly (Blandon et al., 2008; Lunkenheimer et al., 2021; Macfie & Swan, 2009; Maughan et al., 2007; Silk et al., 2006), and elevating the likelihood of psychopathology in later life (Verbeek et al., 2012).

Relatively few studies have focused on the relationships between caregiver anxiety symptoms, caregiver-infant interaction and child emotion regulatory processes. This is despite high prevalence rates of caregiver anxiety, with 15% of caregivers meeting thresholds for clinical anxiety in the year preceding and following birth (Dennis et al., 2017; Leach et al., 2017), and despite the role of affect dysregulation as an etiological (Smith, 2022; Suveg et al., 2010) and maintaining factor in anxiety conditions (Bögels & Lamers, 2002; Brown & McNiff, 2009; Peltola et al., 2016; Thayer et al., 1996). Recent reviews have demonstrated that perinatal[1] anxiety associates with child emotional-behavioural difficulties (Korja et al., 2017; Rees et al., 2019; Spry et al., 2020), such that greater pre- and post-natal caregiver anxiety is related to greater child difficulties with emotion regulation in early and middle childhood. However, these reviews have not addressed the role of caregiver-infant interaction, despite this being a likely explanatory factor in atypical socio-emotional development among infants of anxious caregivers (Feldman, 2007b; Murray et al., 2009). Where scholars have reviewed caregiver-infant interaction and anxiety symptoms, this has involved a narrative rather than systematic approach, precluding methodological quality assessment and a comprehensive examination of the literature (Perlman et al., 2022).

Our existing understanding of how caregivers and children interact to influence each other is rooted in contingency. Contingency is where one partner leads and the other follows, or where one partner anticipates the other's cues, i.e., 'behaviours which occur conditional to the behaviours of the other party' (Wass et al., 2024, p. 31; see also: Beebe et al., 2016).[2] Historically, developmentalists have viewed caregiver-child contingency as optimal for child socio-emotional development. Bowlby and Ainsworth's work highlighted how infants' proximity-seeking behaviour and caregivers' consistent, sensitive responses play a critical role in the development of child attachment security (Ainsworth et al., 2015; Bowlby, 1969; Bretherton, 1985). Later research also suggested the inverse; that less contingency is associated with greater risk, as demonstrated by Field and colleagues' work showing how depressed caregivers displayed less contingent responsivity to their infants, with this being linked to changes in how infants respond to social stressors (Field et al., 2005, 2009). More recently, evidence has suggested very high levels of responsivity to cues may be unhelpful (Bornstein & Manian, 2013). Caregivers' heightened reactivity to neutral or minor instances of negative affect in their infant have been shown to lead to mutually sustained levels of physiological stress in the dyad (Smith, Jones, Charman, et al., 2022), in a pattern akin to what is observed intra-individually in panic

[1]The perinatal period, defined from one year before birth up to 24 months after, is grounded in developmental, attachment, and systems theory frameworks (Austin, 2003; Helfer, 1987). This timeframe is recognised as a critical, or sensitive, period for the establishment of foundational socio-emotional skills in children, including emotional regulation, social interaction, and secure attachment bonds (Feldman, 2015). Theoretical perspectives highlight the importance of this period for long-term developmental trajectories and socio-emotional outcomes (Feldman, 2017a; Ulmer Yaniv et al., 2021; Ulmer-Yaniv et al., 2023). Additionally, the perinatal period is essential for fostering optimal parent-infant interactions, thought to underlie the development of co-regulatory processes and child socio-emotional competencies (DePasquale, 2020; Harrist & Waugh, 2002a; Tronick et al., 1998b; Wass et al., 2024). Optimal early interactions can reinforce both the parent's and child's emotion regulation, potentially leading to improved socio-emotional functioning outcomes; exposure to risk factors during this critical period can interfere with these developmental processes, potentially leading to negative child socio-emotional outcomes and disrupting cohesive family dynamics (Feldman, 2007a, 2007b).

[2]'Contingency' is often used interchangeably with the terms 'responsivity' and 'sensitivity', with the latter particularly common in investigations rooted in attachment theory. Attachment-oriented scholars emphasise an "awareness of infant signals, accurate interpretation [thereof], and prompt response" in their definitions (Beebe & Steele, 2013, p.2).

disorder, i.e., excessive interoceptive response to benign physiological cues (Brown & McNiff, 2009; Clark, 1986). Excessively high levels of contingency may give rise to high levels of stress-matching or ‘synchrony’ in caregivers and infants, a process by which simultaneous neural, behavioural and physiological processes appear to take place between partners (Butler, 2011; Helm et al., 2018).[3] Synchrony is of particular interest to those working within child and adolescent psychopathology, as this is thought to be a central mechanistic factor in the parent-to-child transmission of anxiety (Perlman et al., 2022).

For many psychologists, questions of how caregivers and children interact to influence each other are not new. Developmental scientists now largely conceptualise the development of individual differences in frameworks dominated by environmental, organistic and transactional processes (Granic & Patterson, 2006). This includes, for example, general systems theory (Sameroff, 1983), ecological systems theory (Bronfenbrenner, 1979), the epigenetic model (Gottlieb, 1991), and the transactional model of development (Sameroff, 2010; Sameroff & Fiese, 1990). These systems approaches posit that emotional difficulties ‘come to be expressed and regulated in a relational sense’ (Smith, 2022, p. 29). *Dynamic* system models go beyond this to formally specify how a system changes over time. To do so, scientists make use of a technical terminology originally developed in the fields of mathematics and physics, and now understood as abstract principles that are applied across different disciplines. For example, in developmental psychology, ‘attractors’ represent different stable states or dynamics in which the dyad tends to settle over time (Granic & Patterson, 2006). Elsewhere (Wass et al., 2024, p. 486) we have illustrated what this might look like in practice, i.e., ‘a caregiver-child dyad who tend to get ‘stuck’ in an argument: where the child says something which angers the caregiver, who then says something which angers the child, and so on’. Multiple attractors can co-exist in a single system; when this happens, the system is called ‘multistable’, that is to say, stable in various states. To continue the example: ‘a dyad might show two stable states which, when they are established, tend to persist for a while – such as ‘getting on well’ and ‘stuck in an argument’ (Wass et al., 2024, p. 486). Attractors are thought to emerge partly as a result of feedback loops between caregiver and infant behaviour, as these reinforce patterns of interactions and ultimately develop into a stable state. As such, research based on DST principles typically measures caregiver-child interaction on a moment-by-moment scale (Somers et al., 2020; Zhang et al., 2022, 2023). A theoretical framework based on DST principles has the benefit of focusing attention on the complex, bidirectional and evolving nature of caregiver-infant interactions. From an applied perspective, this is aligned with efforts to develop more holistic and mechanistically precise caregiver-infant psychotherapy interventions.

[3] Contingent interaction is directional (to say that A is contingent on B is not the same as to say that B is contingent on A) whereas synchrony is bidirectional (to say that the A is synchronous with B is the same as to say that B is synchronous with A).

Caregiver-infant interaction is central to the development of emotion regulation (Geva & Feldman, 2008; Tronick, 2002), and this developmental process is altered in the context of caregiver difficulties with emotion regulation - a characteristic of anxiety conditions, which we know are prevalent in the perinatal period (Dennis et al., 2017; Leach et al., 2017). It is therefore important to establish how caregiver anxiety relates to caregiver-infant interaction dynamics. To address this, I systematically reviewed the association between caregiver-infant interaction and perinatal anxiety, focusing on methodologies including a time dimension. Where possible, I examined how the interaction between anxious caregivers and infants differs depending on stage of development, how caregiver-infant interaction relates to infant socio-emotional development, and how this latter relationship might be affected by wider contextual factors.

2. Method

2.1 Eligibility criteria including outcomes of interest

To examine the relationship between perinatal anxiety and caregiver-infant interaction dynamics, I sought to identify all relevant peer reviewed papers. The study protocol was preregistered and submitted to PROSPERO on 2 February 2023 (registration number: CRD42023395663). Two amendments to the protocol were submitted on 14 July 2023 and 21 August 2023. Eligible studies were quantitative, following a longitudinal or cross-sectional design (including case-control or cohort designs) and written in English. Studies were eligible if participants met the following criteria: (a) caregivers or pregnant people, of any age or gender, at elevated likelihood of or meeting criteria[4] for anxiety disorders (including obsessive-compulsive disorder and specific phobia); (b) infants under and up to 24 months of age; typically developing at full term, without prior care in neonatal intensive care.

For the primary and secondary research questions, the outcome I wished to examine was caregiver-infant interaction. Specifically, eligible studies were those where the caregiver-infant interaction dynamic was included as an outcome variable. This was operationalised as temporal relatedness, measured using observations of dyadic processes with near-continuous (i.e., moment by moment) ratings or recordings of both member of the dyad’s behaviour or physiology over a set time interval. Though I was also interested in factors moderating the relationship between perinatal anxiety and caregiver-infant interaction, or elucidating the pathway between perinatal anxiety, caregiver-infant interaction, and child socio-emotional functioning, I expected the literature regarding these would be sparse. Moderating and mediating factors were therefore not specified within eligibility criteria. For full details regarding exclusion criteria, see Appendix section 1.

[4]This criterion encompasses both categorical and dimensional approaches to conceptualising psychopathology, thus including both diagnosed anxiety disorders and samples containing parents with elevated anxiety traits.

2.2 Search strategy

The search strategy comprised both hand and electronic database searching. The finalised electronic search was carried out on 14 July 2023, via OvidSP: EMBASE, APA PsychINFO, MIDIRS and Medline. Search terms to identify the population and exposure were: (parent* adj5 (mental* ill* or mental* disorder* or mental health or mood disorder* or affective disorder or anxi* or depress* or OCD or obsessive compulsive disorder or PTSD or post traumatic stress disorder or trauma)) OR exp Parents/ and (exp Mental Disorders/ or exp Mental Health/ or exp Mood disorders/) AND to identify the outcome: exp Parent-Child Relations/ or exp Child Rearing or exp Infant Behavior/ or exp Infant development/ OR ((mother* or maternal or father* or paternal) adj5 (infant* or baby or child*) adj5 (interact* or relations* or bond* or develop*)). Field searching was expansive (using mp. versus ti.ab) to avoid omitting studies where criteria were mentioned in the main text. After this, reference list searching and citation searching were conducted by hand (the latter informed by recent guidance on the use of web search tools; Briscoe et al., 2020).

2.3 Screening procedure

Records retrieved from electronic and hand searching were downloaded into bibliographic software (Zotero Desktop Reference Manager, version 6.0.26). An online web application (see 'Deduplicator', Rathbone et al., 2015) was used to automatically remove identical duplicates, with all records subsequently checked by hand by the lead author. All records where then screened by title and abstract according to the eligibility criteria, with a second screener rating 20% of records independently. Classification options were: ‘Include, ‘Exclude,’ or ‘Maybe’, with the latter reserved for records where information for one inclusion criterion was ambiguous. Calculations of accuracy were based on included records; disagreements were identified using an automated web tool (see ‘Disputatron’; Clark et al., 2020; Scott et al., 2021, 2023). The full text of all records marked included or maybe were screened by CS, with 20% screened independently by a second rater (percentage agreement 96.6%, kappa = 0.78); discrepancies were resolved by a third team member.

2.4 Data extraction procedure

A data extraction worksheet was developed based on the Cochrane Collaboration data extraction form for non-randomised controlled trials (Cochrane Collaboration, 2014). Extracted data included: primary author, year of publication, sample characteristics (sample size, recruitment, inclusion criteria, caregiver and infant age and gender, country, ethnicity, socio-economic status), measure of caregiver anxiety (diagnostic classification *vs*. self-report), measure of caregiver-infant interaction dynamic (including statistical approach used), task characteristics (e.g., neutral vs negative condition during which interaction was measured), system level (physiology *vs*. behaviour), any moderating/mediating factors (if applicable) and main findings. A second researcher checked extracted data against included records for the following fields: study design, sample (total N, recruitment), child age, system level, task characteristics, measure of caregiver-infant dynamic including statistical approach used, main findings, any moderating/mediating factors. Several studies (N = 6) included a homogeneous measure of the outcome of interest (i.e., measuring caregiver-infant interaction as 'synchrony'). Though a meta-analysis was planned for such a scenario during preregistration, insufficient information available from reports and study authors whom I contacted led to very few eligible studies (k = 4). This raised issues of low power and the potential for over-conservatism in estimates of the observed outcome (Bender, 2023). Consequently, a qualitative synthesis was selected as the primary approach, with the meta-analysis included as a complement to this.

2.5 Synthesis of results

2.5.1 Qualitative synthesis

To organise findings from all nine included studies and to describe patterns across these in terms of direction and size of associations, narrative synthesis was used to address the primary research question (Popay et al., 2005). This approach also allowed us to examine factors that might explain differences in the strength of associations across studies (e.g., developmental stage, co-occurring parental mental health conditions and task characteristics). One factor of interest, 'family involvement' was excluded from the qualitative synthesis due to insufficient data available across included studies.

2.5.2 Quantitative synthesis

Studies included in the meta-analysis were generally expected to be from diverse populations, thus a random-effects meta-analysis was performed using R software (version 4.3.1) and the metafor package (Viechtbauer, 2010). The total amount of variability among the true outcomes was estimated using the restricted maximum-likelihood estimator (Viechtbauer, 2005). Statistical heterogeneity was tested by calculating the Q (Cochran, 1954) and I^2 statistic (Higgins & Thompson, 2002); a prediction interval for the true outcomes was also computed (Riley et al., 2011). These statistics are known to underestimate heterogeneity when the k is small; subsequently, risk of bias was also assessed within studies. To examine whether studies could be outliers, or could be influential in the context of the model, Viechtbauer and Cheung's (2010) approach to studentized residuals and Cook's distances were used. The outlier detection strategy was based on established procedures (Viechtbauer & Cheung, 2010). Specifically, studies judged to be potential outliers were those whereby the studentized residual was greater than $100\times(1-0.05/(2\times k))$th centile of a standard normal distribution (a Bonferroni correction with two-sided α=.05 for the 4 studies included). In addition, studies included in the meta-analysis that had a Cook's distance of greater than the median plus 6*IQR of the

Cook's distances were deemed influential. In the case of significant heterogeneity ($p < .05$ for Cochran's Q, or $I^2 > 50\%$; Deeks et al., 2022), I planned to use sensitivity analyses to explore the source of heterogeneity. Given the small number of included studies in the meta-analysis (<10), meta-regression analyses for examining moderator variables were not conducted to prevent the risk of spurious findings (Higgins & Thompson, 2004).

Regarding summary measures, the primary effect size measure of the strength of the association between perinatal anxiety and caregiver-infant synchrony was correlation coefficient (*r*). Fisher's Z-to-r transformation was used to stabilise variances. Where a correlation between variables of interest was not reported in an included study, *r* was calculated using an online tool via means and standard deviations or sample sizes and t-test values (Lipsey & Wilson, 2001). Four reports represented two studies (Lotzin et al., 2015, 2016; Smith et al., 2022, 2023). I selected the primary report for inclusion based on the degree of similarity to the remaining eligible studies within the exposure and outcome measures (Lotzin et al., 2015; Smith, Jones, Charman, et al., 2022). In addition, one study reported multiple effect sizes regarding the association between perinatal anxiety and caregiver-infant synchrony (Granat et al., 2017). In this case, I computed a synthetic effect size (an average effect size with a variance taking account of the correlation among different outcomes; Borenstein et al., 2021).[5] One study provided an effect size at two time points – one before and after the stressor had taken place (Lotzin et al., 2015); in this instance, I chose the first time point to promote uniformity in the synchrony measures (the majority of which were administered in a neutral rather than negatively valenced task). Finally, insufficient information was available from three studies to allow extraction of the required statistical values; in these cases, study authors were contacted. Four studies were subsequently included in the meta-analysis; these four studies and the remaining five studies were subsequently synthesised narratively in the systematic review.

2.6 Risk of bias

Risk of bias within studies was determined using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (National Heart Lung and Blood Institute, 2014), adapted for relevance to intergenerational cohorts (Spry et al., 2020). The tool comprises 11 criteria, for which each criterion requires a yes/no/unknown judgement (see Appendix, Supplementary Table 1). All the risk of bias assessments were also performed independently by a separate reviewer to identify any discrepancies and reach consensus judgements. Risk of bias was assessed qualitatively without generating a total score, as use of summary scores to identify quality is thought to be problematic (Jüni et al., 1999). To examine publication bias within the meta-analysis, I used the rank correlation

[5]In calculating the average of six correlation coefficients - four positive, two negative - I applied an inversion to two negative correlation coefficients. Calculating an average without an inversion may have led to partial cancellation and concealed the directional trend indicated by the positive coefficients.

test and the regression test to check funnel plot asymmetry (Begg & Mazumdar, 1994; Sterne & Egger, 2005).

3. Results

3.1 Search results

The total number of records identified from electronic searches was 5064. Duplicates were removed, leaving 3752 records to be screened by title and abstract. Of these, 3589 ineligible records were excluded, with the 163 remaining articles retrieved to be screened by full text. Accuracy measures from two independent reviewers suggested high inter-rater reliability (percentage agreement and prevalence and bias adjusted kappa, 97.2%, $\kappa = .94$). The following were excluded: 24 articles where child age was too old; 20 articles where the interaction measure was self-report, 64 articles where the interaction measure was time invariant and 8 articles where there was no direct interaction measure (e.g., an infant was presented with pictures of faces on an eye-tracker). Conference abstracts (18), dissertations (10) and book chapters (1) were also excluded, as were articles not written in English (4). One duplicate not previously identified was also excluded. The full texts of five records retrieved from the manual search were also screened, with one excluded due to the interaction measure being self-report. Finally, 11 reports (nine studies) were included in the systematic review, seven via the electronic search and four from the manual search. Of the nine studies, four were included in the meta-analysis of caregiver-infant synchrony. The full screening results for the systematic review are displayed in Figure 1 (PRISMA diagram).

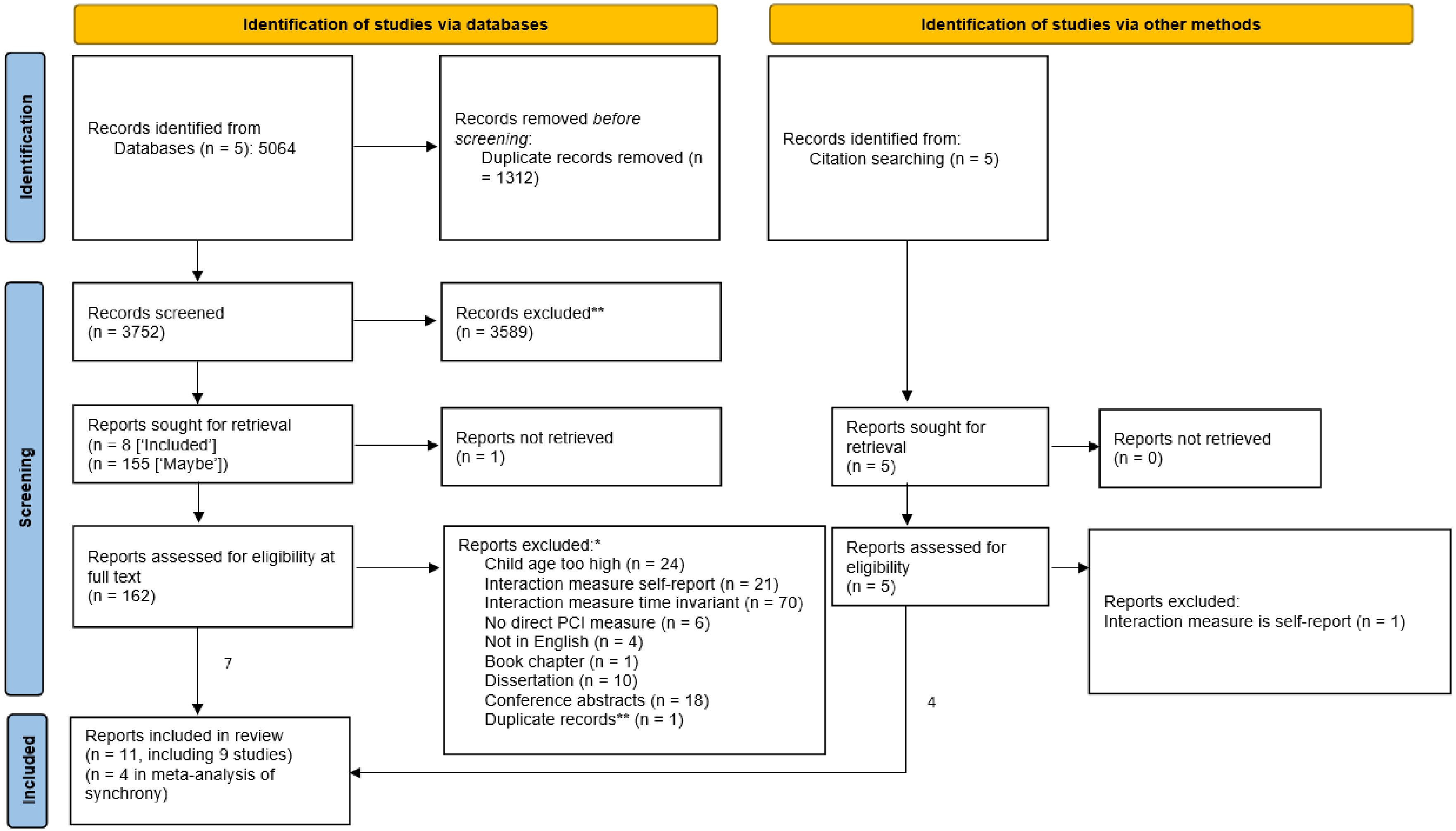

Figure 1. PRISMA flow diagram adapted from Page and colleagues (2021).

Notes
*Indicates at least one unmet inclusion criterion per record; multiple records did not meet >1 inclusion criteria – see Table S2 in Appendix for details.
**Indicates that the record was not removed in identification phase due to inconsistent metadata.

3.2 Study characteristics

A total of 845 participants were included in the systematic review (11 reports; 9 studies), with 329 participants in the meta-analysis of caregiver-infant synchrony.[6] The main study characteristics are presented in Table 1. Of the nine studies, seven were from European or North American populations and two were from the Middle East and North Africa region. There was variation in the demographic information reported across studies. Two studies were based on diverse populations, with 47-53% identifying as from a minoritised ethnic background (Beebe et al., 2011; Smith et al., 2022, 2023), with the remainder representing majority ethnic groups (Kaitz et al., 2010; Lotzin et al., 2015, 2016; Ostlund et al., 2017) or not reporting ethnicity data (Doba et al., 2022; Granat et al., 2017; Holmberg et al., 2020; Hsu, 2004). Participants were recruited from general hospitals (54%), a mixture of general hospital and state-funded assistance programmes (22%), psychiatric hospitals (8%), university and nursery settings (8%), and caregiver education groups (6%). Caregiver participants in all studies were women of working adult age, and all infants were under the age of 12 months at study entry; infant gender was approximately equally balanced in all studies. Most studies focused on postnatal anxiety with eight studies assessing postnatally and one assessing both prenatal and postnatal anxiety. All studies included a self-report measure of caregiver anxiety, though not all reported means and standard deviations; in these cases, caregiver anxiety was measured and reported on the basis of diagnostic interview (Granat et al., 2017; Kaitz et al., 2010; Lotzin et al., 2015, 2016).

Of the nine studies in the systematic review, seven studies reported a measure of depressive symptoms. Five included a self-report measure (Doba et al., 2022; Holmberg et al., 2020; Hsu, 2004; Kaitz et al., 2010; Ostlund et al., 2017) with scores falling outside the clinical and subclinical range (EPDS, BDI; Leigh & Milgrom, 2008; Levis et al., 2020). Two studies included a diagnostic interview; one separated participants into an anxiety *vs* depression *vs* control group (Granat et al., 2017), while the other identified participants meeting criteria for depression and co-occurring anxiety (Lotzin et al., 2015, 2016). Two studies did not report a measure of depressive symptoms (Beebe et al., 2011; Smith et al., 2022, 2023).

[6]The figure 845 refers to the total number of participants across the nine samples of the eleven reports included in the systematic review (all recruitment percentages cited hereafter are based on these nine samples). The figure 329 refers to the total number of participants upon which effect sizes were based across the four studies included in the meta-analysis.

Table 1. Study characteristics

Author, year	**Design and recruitment**	**Sample (N, % BME, SES, mean ages)**	**Caregiver anxiety measure and characteristics**	**Task characteristics and location**	**System level**
Hsu, 2004	Longitudinal.[a] Prenatal education classes, USA	*N* = 53 % BME: 0, reports 'all white' % higher education, income: NA[b] Caregiver M age (y): 27.28 Child M age (m): 3[c]	Self-report, MSA scale, *M* = 22.05, *SD* = 4.08[d]	Neutral (free play, 15 min x 2) Home-based	Behaviour
Beebe, 2011	Cross-sectional. Urban University Hospital, USA	*N* = 119 % BME: 47 % higher education: 59.1 % sample < $20k / £16k: NA Caregiver M age (y): 29.0 Child M age (m): 4	Self-report, STAI-T collected 4m postpartum, *M* = 33.72, *SD* = 9.05 Using IQR, 'Elevated anxiety' defined as upper 25% of participants, scoring ≥40; 'Low anxiety' defined as lower 25% scoring ≤27	Neutral (table-top free play, 10 min) Lab-based	Behaviour
Ostlund, 2017	Cross-sectional. Local hospitals, public assistance organisations, USA	*N* = 95 % BME: 19 % higher education: 54 % sample < $20k / £16k: 41 Caregiver M age (y): 24.5 Child M age (m): 5.19	Self-report, BAI collected 5m postpartum, *M* = 6.57, *SD* = 6.96	Negative (still face paradigm, initial phase 2 min, still face 2.5 min, reunion phase 1 min) Lab-based	Physiology
Doba, 2022	Cross-sectional. University Hospital, Lille, France	*N* = 72 % BME: NA % higher education: 58.2 % sample < $20k / £16k: NA Caregiver M age (y): 30.72 Child M age (m): 6	Self-report, STAI-S collected 6m postpartum, *M* = 36.61, *SD* = 9.92 23.6% rated above the cut-off score (≥46) for anxiety symptoms	Mixed: (1) table-top free play, 10 min; (2) free play, 10 min, after 3 min caregiver separation & stranger present Lab-based	Behaviour

Kaitz, 2010[†]	Case control. Urban hospitals, government-funded ‘well-baby’ clinics, Israel	*N* = 93 (34 AD, 59 CG) % BME: 76.5 native Israeli; all Jewish[f] % higher education: 76.4 % sample < $20k / £16k: NA Caregiver M age (y): 26.06 Child M age (m): 6	Clinician-administered SCID-I diagnostic interview and BAI at 6m postpartum; anxiety group were 13 with panic, 8 with social phobia and 12 with PTSD (no depression)	Negative (still face paradigm, 2 min initial phase, 2 min still face phase; 2 min reunion) and 2 min stranger-infant face to face play Lab-based	Behaviour
Lotzin, 2015[†]	Cross-sectional. Mother–infant outpatient psychiatric unit, University Medical Centre of Hamburg, Germany	*N* = 68 % BME: 1.5 % higher education: NA[f] % sample < $20k / £16k: 13.2 Caregiver M age (y): 32.2 Child M age (m): 6.3	Researcher-administered SCID-I diagnostic interview (postpartum) and self-report, either SCL-90-R anxiety subscale (2015) or GSI of SCL-90 (2016) 55.9% caregivers met criteria for anxiety disorders (GAD, social phobia, specific phobia, or panic disorders, OCD, PTSD) and co-occurring mood disorder, all other caregivers met criteria for mood disorder	Negative (still face paradigm, initial phase 3 min, still face 1 min, reunion phase 3 min) Lab-based	Behaviour
Lotzin, 2016					Behaviour
Holmberg, 2020	Case control.[a] Nationwide hospitals, Finland	*N* = 177 % BME: NA % higher education: 38.4 % sample < $20k / £16k: 33.9 Caregiver M age (y): 31.18 Child M age (m): 8	Self-report, SCL-90 anxiety subscale collected pre and postnatally, *M* = 3.63, *SD* = 4.05 ‘Elevated anxiety’ defined as highest 10^{th} percentile at each timepoint	Neutral (free play, floor-based, 10 min) Lab-based	Behaviour
Granat, 2017[†]	Extreme case design. Large metropolitan hospitals, Israel	*N* = 100 (19 AD; 69 CG, 22 MDD) % BME, higher education, income: NA[g] Caregiver M age (y): 30.7	Clinician-administered SCID-I diagnostic interview at 9m	Neutral (free play, floor-based, 6 min)	Behaviour

		Child M age (m): 9	postpartum, and STAI-T (*M, SD* = NA). All in AD group met diagnostic criteria for GAD, social phobia, specific phobia, or panic disorder	Lab-based	
Smith, 2022[†]	Cross-sectional. Universities, nurseries and caregiver-baby groups in the capital and neighbouring regions, UK	*N* = 68 % BME: 53 % higher education: 74[e] % sample < $20k / £16k: 31 Caregiver M age (y): NA Child M age (m): 12	Self-report, GAD-7 collected 12m postpartum. Median split to create lower anxiety (*M* = 0.76, *SD* = 0.85) and higher anxiety (*M* = 6.16, *SD* = 3.96) groups	Neutral (naturalistic time together when at home, awake – no researcher present) Home-based	Physiology
Smith, 2023					Physiology

Notes

In ascending order by infant age.

NA = not reported; AD = Anxiety Disorder group; CG = Control Group; MDD = Major Depressive Disorder group.

[†]Included in meta-analysis of caregiver-infant synchrony

Sample characteristics: sample size; percentage of sample identifying as black or from a minoritised ethnic background (BME); percentage of caregivers who had attended higher education; percentage of sample where the household income is less than £16, 000; mean age of caregiver in years; mean age of infant in months.

[a]Longitudinal study with relevant cross-sectional data.

[b]Education not categorised; participants completed on average 15.3 years of education (*SD* = 2.24).

[c]Child age at timepoint 4 when caregiver-infant interaction data collected.

[d]Maternal Separation Anxiety scale (Hock et al., 1989) collected at 1 and 3 months postpartum; former included only as this was used for analyses of caregiver-child interaction.

[e]All sample characteristics from anxiety group; no significant differences between anxious *vs* non-anxious group on demographic variables.

[f]Education not categorised; participants completed on average 15.2 years of education (*SD* = 3.0).

[g]Education not categorised; participants completed on average 15.8 years of education (*SD* = 2.6).

State Trait Anxiety Inventory, Trait (STAI-T) and State (STAI-S; Spielberger, 1983; Spielberger et al., 1970); Structured Clinical Interview, DSM-IV-R Axis I disorders (SCID-I; First & Gibbon, 2004); Symptom Checklist-90 [Revised] (SCL-90, SCL-90-R) anxiety subscale, Global Severity Index (GSI) where GSI measures multiple broad dimensions e.g. anxiety, phobic anxiety, obsessive-compulsive symptoms, hostility, somatisation, interpersonal sensitivity, paranoia (Derogatis et al., 1974; Franke, 2002; Holi et al., 1998), Generalised Anxiety Disorder Screening tool (GAD-7; Spitzer et al., 2006); Beck Anxiety Inventory (BAI; Beck & Steer, 1991); Generalised Anxiety Disorder (GAD); Social Anxiety Disorder (SAD); Obsessive-compulsive disorder (OCD): Post-traumatic stress disorder (PTSD). Clinical cut-offs for dimensional scales include: STAI = 43+ (for postnatal anxiety risk; Gilboa et al., 2004); BAI = 10 (mild to moderate anxiety); GAD-7 = 6+ (mild to moderate anxiety).

3.3 Quality assessments

Risk of bias in each study was evaluated across multiple items related to sampling, measures, and analyses (Appendix, Table S1). Regarding sampling, four studies (44%) provided power estimates and six studies (66%) met adequate attrition rates (<39%). However, seven (77%) studies used convenience or single-site sampling, and seven studies defined the study population unclearly (although this was mainly a result of missing the specific dates between which participants were recruited; general timeframes were indicated, e.g., the day after giving birth). Detailed demographic information (i.e., at least two from the categories of ethnicity, household income, occupation, or education for caregiver, and at least gender and age for infant) was provided in four (44%) studies.

Regarding measures, all nine studies (100%) included caregiver anxiety measures that have been demonstrated to be valid, reliable tools. Six studies (66%) included a subjective measure (i.e., caregiver self-report) with the remaining three using researcher or clinician-administered diagnostic tools, which I considered an objective measure. Six studies (66%) also used multiple methods to assess the outcome. None of the studies used a pre-established outcome measure for caregiver-infant interaction; as dynamic systems approaches are novel in this field, and data with a time dimension are highly complex, this was anticipated. Regarding analyses, there was variation in the management of confounding variables: in seven studies (77%) I was able to identify evidence of analyses that controlled for caregiver and infant characteristics. I was also able to identify four (44%) studies in which missing data was accounted for. Further details of the quality assessments are provided in the Appendix (Table S1).

3.4 Synthesis of results

The following sections detail the results of the quantitative synthesis, i.e., the meta-analysis (3.4.1) and the qualitative synthesis, i.e., the systematic review (sections 3.4.2 to 3.4.7).

3.4.1 Meta-analysis: perinatal anxiety x synchrony

I found a significant pooled effect size of $r = .16$ ($p = .02$, 95% CI .03, .29) regarding the association between perinatal anxiety and caregiver-infant synchrony ($k = 4$). Though the effect was small, perinatal anxiety was therefore associated with an increase in caregiver-infant synchrony. The prediction interval (estimating the range in which an effect will be observed in 95% of studies in the future) was -.02 and .34, thus indicating some uncertainty in the significance of the result. This is despite heterogeneity among studies being low ($Q = 3.68$, $p = .30$, $I^2 = 22.73\%$). The results are presented in Figure 2. None of the studies were considered overly influential according to Cook's distances. No outliers were detected on examination of studentized residuals (no studies had a value >2.50). Figure 3 presents a funnel plot of the estimates; neither the rank correlation ($p = .07$) nor the regression test ($p = .06$) indicated funnel plot asymmetry. The small k of the meta-analysis prevented formal investigation of the extent to which various study characteristics modified the positive relation between caregiver anxiety and caregiver-infant synchrony.

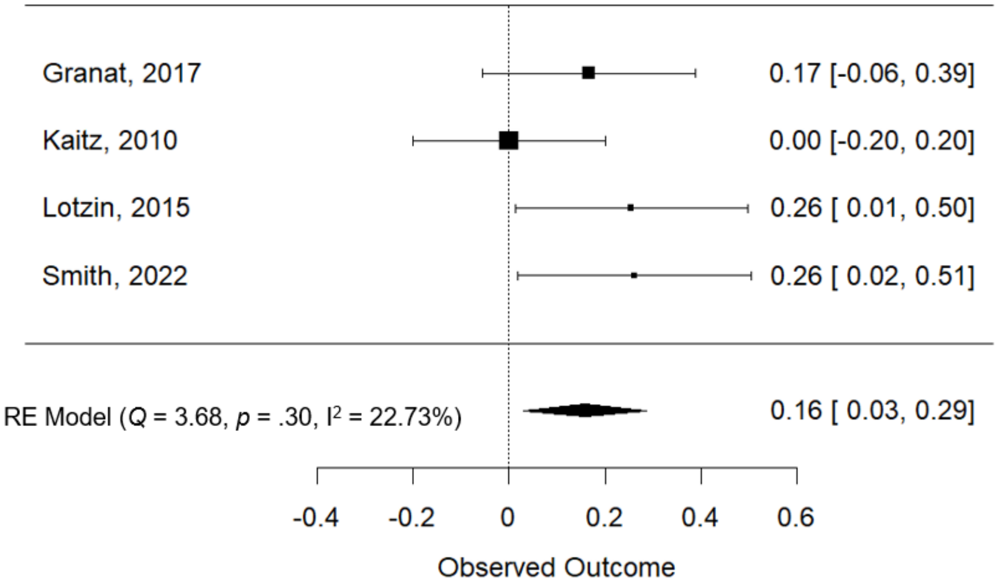

Figure 2. Forest plot showing results of the random effects (RE) model, including correlation coefficient ($r = 0.16$), 95% confidence intervals (0.03, 0.29), and heterogeneity statistics (Cochran's Q and I^2; significant heterogeneity is judged from a significant p value for Q, or in the case that I^2 = >50%).

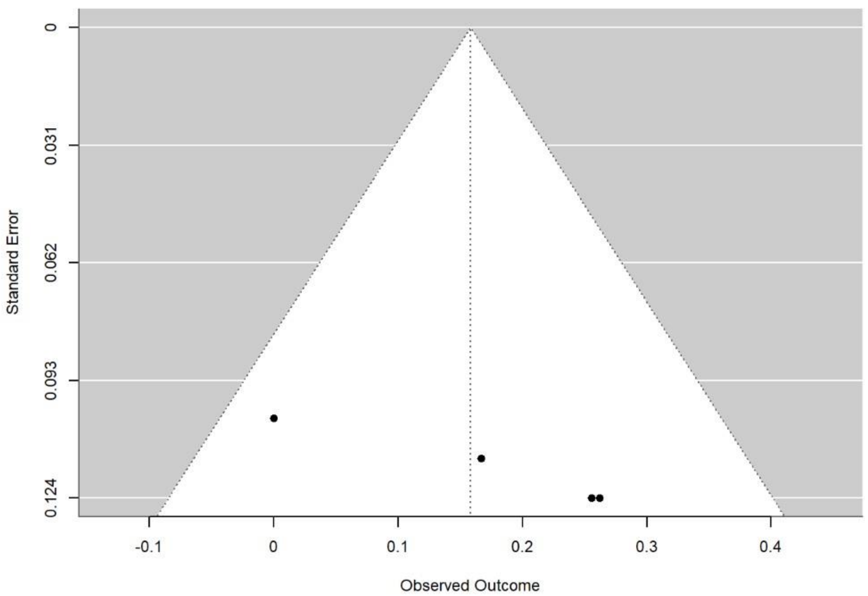

Figure 3. Funnel plot: diagonal lines represent 95% confidence intervals around the summary estimate for each standard error on the vertical axis. The scatter shows: 'the expected distribution of studies in the absence of heterogeneity or selection biases … in the absence of heterogeneity, 95% of

the studies should lie within the funnel defined by these straight lines' (Sterne & Harbord, 2004, p. 131).

3.4.2 Strong to moderate associations: perinatal anxiety x synchrony

Six studies examined the association between perinatal anxiety and caregiver-infant synchrony, i.e., the phenomenon by which simultaneous neural, behavioural, or physiological processes appear to take place between the dyad (with corresponding definitions for synchrony presented by study in Table 2). Of these, three studies demonstrated medium to strong sized relationships. In Doba and colleagues' (2022) cross-sectional, community sample of caregivers recruited from the University hospital (with scores indicating, on average, subclinical levels of anxiety and, in a quarter of cases, clinical levels), the authors found a strong direct effect between caregiver anxiety and caregiver-infant synchrony at six months postpartum (β = .58), with synchrony measured as the latent variable of motor, verbal, gaze synchrony across both a neutral and stress induction task. Of note, no direct association was observed between self-reported depressive symptoms in caregivers and caregiver-infant synchrony. By contrast, in their study of mothers referred to a mother-infant outpatient psychiatric unit, Lotzin and colleagues (2016) reported a significant, medium-sized relationship between caregiver-infant facial affect synchrony and caregivers with co-occurring anxiety and mood disorders, such that synchrony levels were higher between caregivers and their infants *vs.* caregivers and randomly assigned infants during both a neutral task (d = .38) and after a stressor (d = .30).

In Smith and colleagues' diverse community sample of caregivers studied in a naturalistic environment (2022, 2023), caregivers with higher scores of self-reported anxiety demonstrated higher physiological synchrony with their infants across the course of a day at home compared to caregivers with low scores (r = .26; 2022). Similarly, when performing within-group analyses on the most elevated peaks in physiological arousal, the authors found evidence for caregiver-infant synchrony in the form of co-occurring arousal peaks in caregivers and infants within the high but not the low anxiety group (r = .28; 2023). In addition, Smith and colleagues found that an index of infant emotion regulation was related to caregivers' reactivity to minor changes in infant stress (rho = −.33) such that greater infant emotion dysregulation was observed among dyads where caregivers over-responded to small-scale fluctuations in infant stress (a characteristic observed independently in the anxiety group; Smith et al., 2022).[7] Authors also found evidence for a relationship between high levels of sustained physiological stress among infants in the high anxiety (but not low anxiety) group after caregivers uttered high-intensity vocalisations (effect size incalculable; Smith et al., 2023).

[7]Emotion regulation index = infant recovery following instance of spontaneous negative affect.

3.4.3 Moderate to small associations: perinatal anxiety x synchrony

Two of the six studies examining caregiver-infant synchrony and perinatal anxiety demonstrated weak to medium sized relationships. In Granat and colleagues' (2017) extreme case design examining caregivers with clinically diagnosed anxiety disorder *vs.* major depressive disorder *vs.* controls (neither diagnosis), authors observed caregivers interacting with their nine-month-old infants in a neutral, lab-based behavioural paradigm. The authors found that anxious caregivers and infants demonstrated significantly higher levels of touch synchrony by latency (i.e., how quickly they reached onset of a synchronous episode; r = -.30) and frequency (r = .41) than the depression group. Anxious caregivers were also found to spend longer in gaze-synchronous episodes (r = .16) and be quicker to begin such episodes than controls (r = -.17), though effects were non-significant. In general, across gaze and touch modalities, the authors found that caregivers with anxiety exhibited the highest levels of synchrony with their infants, with depressed caregivers scoring lower, and controls scoring in the mid-range between the two diagnostic groups. Correlation coefficients were not reported, but inspection of means, standard deviations and group sizes indicated weak to medium sized associations.

In Kaitz and colleagues' (2010) case control study examining time series relations between clinically diagnosed anxious caregivers and their infants during two stress induction tasks *vs.* a control group, weaker associations were found between caregiver anxiety and caregiver-infant synchrony. Authors did not report most Group/Group x Episode results due to finding no significant effects. An exception is the report of an analysis of positive affect synchrony (termed 'matching' in the report). Results suggested a stronger decline in levels of synchrony after the introduction of a stressor for control dyads, compared to dyads in the anxious group: $F(1, 85) = 3.33$, $p = .071$, $\eta p^2 = .04$. Of note, the anxiety group were a diagnostically homogeneous group with no co-occurring depressive symptoms (Kaitz et al., 2010).

3.4.4 No association: perinatal anxiety x synchrony

Two of the six studies examining caregiver-infant synchrony and perinatal anxiety indicated no association. In Ostlund and colleagues' (2017) cross-sectional study of a community sample with, on average, minimal levels of caregiver anxiety, anxiety symptoms were unrelated to physiological synchrony ($\beta < -.01$, SE = .01, $p = .61$), as were depressive symptoms ($\beta = -.02$, SE = .03, $p = .41$). In Lotzin and colleagues' (2015) cross-sectional study of a clinical sample where approximately half of the participants had co-occurring depression and anxiety diagnoses, anxiety symptoms were unrelated to behavioural caregiver-infant synchrony after computing a best-fitting model, including caregiver depressive symptoms, emotion dysregulation, task condition and other demographic variables (random effect estimate = .05). Depressive symptoms in the best fitting model were also unrelated to synchrony (random effect estimate = .05).

3.4.5 Developmental course: perinatal anxiety x synchrony

Four of the six studies examining caregiver-infant synchrony explored the relationship between perinatal anxiety and synchrony when the infant was six months old or younger (Beebe et al., 2011; Doba et al., 2022; Kaitz et al., 2010; Lotzin et al., 2015, 2016; Ostlund et al., 2017). Ostlund and colleagues (2017) found caregiver anxiety symptoms were unrelated to physiological caregiver-infant attunement when infants were approximately 5 months old. When infants were approximately 6 months old, medium to strong sized relationships between caregiver anxiety and behavioural measures of caregiver-infant synchrony were observed (e.g., Doba et al., 2022; Lotzin et al., 2016), with moderate associations and statistical significance reached except for the best-fitting model (Lotzin et al., 2015). Weaker and marginally significant relationships between caregiver-infant synchrony and caregiver anxiety at six months postpartum were also observed (Kaitz et al., 2010).

Two studies explored the association between perinatal anxiety and caregiver-infant synchrony when the infant was over six months old. These studies found that dyads belonging to the ‘high anxiety’ group demonstrated higher levels of physiological synchrony (infant age 12 months; Smith et al., 2022, 2023) and gaze/touch synchrony with respect to how quickly dyads reached an episode of synchrony (8 months; Granat et al., 2017) compared with the low anxiety or control group. Significant, medium to strong relationship sizes were observed.

3.4.6 Perinatal anxiety and caregiver contingency

Three of the studies included in the systematic review reported outcome measures that were not defined as synchrony, but rather were related to contingency in caregiving behaviour.[8] Hsu and colleagues’ longitudinal study set within the community examined responsive interactions, i.e., the caregiver’s ability to ‘provide appropriate, contingent and consistent care’, operationalised as a change in caregiver behaviour within three seconds of the infant’s behavioural signal (Hsu, 2004, p. 116). Holmberg and colleagues’ case-control study measured unpredictable interactions, defined as a lack of consistency in the order of caregiver sensory signals – i.e., the opposite of ‘continuous and emotionally predictable care’ (Holmberg et al., 2020, p. 2). Details of the recruitment, tasks, exposure and outcome measures as well as statistical analyses used are detailed in Tables 1 and 2. Results indicated a weak to medium sized positive relationship between prenatal anxiety and more unpredictable caregiving (β = .197, p = .007; Holmberg et al., 2020). Hsu and colleagues (2004) also found medium sized positive relationships between postnatal anxiety and the degree of responsivity to infant behavioural signals (β = .40, $p < .05$); the greater the caregiver anxiety, the higher the caregiver responsivity to infant negative signals, and the lower the responsivity to infant positive signals (β = -.31 $p < .10$). All results reached or margined on statistical significance. No association between caregiver depressive symptoms and unpredictable caregiving was observed by Holmberg and

[8]Further detail on the conceptual disaggregation of contingency and synchrony is given on pages 9, 10 and 76.

colleagues (2020), and there was no investigation of the association between caregiver depression and caregiver-infant interaction by Hsu and colleagues (2004).

Further weak relationships were broadly observed in Beebe and colleagues (2011) cross-sectional study of a community sample recruited from an urban University hospital (with scores indicating, on average, subclinical levels of anxiety and, in a quarter of cases, clinical levels). When authors compared the sample's 25% highest scorers ('high anxiety') on the self-report anxiety measure with the sample's 25% lowest scorers ('low anxiety'), results showed a small association between caregiver anxiety and facial affect contingency (β = .03) and cross-modal affect contingency (β = -.004), such that more anxious caregivers displayed higher levels of contingency with infants' facial affect, and lower levels of contingency between different behavioural signals of affect (i.e., infant vocalisation *vs.* caregiver facial expression). When authors compared caregivers with high anxiety with caregivers whose scores fell in the mid-range, results demonstrated that the infants of more anxious caregivers displayed less contingency of facial affect with their caregivers (β = -.014) and less contingency of cross-modal affect (infant vocal affect *vs*. caregiver facial affect; β = -.32). Infants of more anxious caregivers displayed further contingency cross-modally (e.g., infant vocal affect *vs.* caregiver touch), when compared to infants of caregivers whose anxiety scores fell in the mid-range (β = .06). No associations were found between caregiver anxiety and caregiver-infant contingency across other behavioural domains (gaze, touch and spatial proximity; all β < .081, all *ps* > .05). The authors did not include a measure of depressive symptoms in the study, precluding disentanglement of potential effects of caregiver mood *vs.* anxiety.

3.4.7 Moderating and mediating factors

None of the studies formally examined the relationship between caregiver anxiety, caregiver-infant interaction, and child socio-emotional functioning; as such, it was not possible to examine whether caregiver-infant interaction represented a mediating variable on the path from perinatal anxiety to child socio-emotional functioning, nor whether there were moderating factors that altered the strength of the relationship between perinatal anxiety and caregiver-infant synchrony. Where studies did examine relationships of moderation and mediation, these were primarily related to caregiver emotion regulation difficulties as a factor underlying the association between caregiver anxiety and caregiver-infant interaction. One study found that caregiver self-regulation capacity moderated the relation between perinatal anxiety symptoms and unpredictability in caregiving behaviour, such that lower regulation increased the predictive relation between anxiety and unpredictability (large relationship; Holmberg et al., 2020). Another study found that increased caregiver emotion regulation difficulties associated with heightened maternal anxiety, leading in turn to higher levels of caregiver-infant synchrony (medium-large relationship; Doba et al., 2022). In addition, one study examined the moderating effects of several demographic factors (caregiver age, education and infant gender) on the relationship between caregiver anxiety and caregiver-infant synchrony; all relationships were minimal to weak and non-significant (Doba et al., 2022).

Table 2. Study outcomes

Author, year	**Outcome measure, i.e., caregiver-infant (CCI) construct**	**Statistical analysis**	**Patterns and findings**	**Results – perinatal anxiety x CCI**	**Results – perinatal depression x CCI**
Hsu, 2004	Caregiver responsivity: ‘ability to provide appropriate, contingent, and consistent care… a mother’s action was credited as responsive when she made a change in her ongoing behavior within 3 s of her infant’s facial and/or vocal signal’ (p. 116)	Conditional probabilities	[1] Postnatal anxiety associated positively with parental responsivity to infant behavioural signals [2] The greater the caregiver anxiety, the higher the caregiver responsivity to infant negative signals, and the lower the responsivity to infant positive signals	Medium-sized relationships (+/-) [1] β = .40, p < .05 [2] β = -.31 p < .10	NA
Beebe, 2011	Interactive contingency: ‘mirroring’ … ‘degree to which partner follows the direction of each other’s [behaviour]’ … ‘chase and dodge dynamic’ (pp. 179-80)	Multi-level time-series models	Comparing high *vs.* low caregiver anxiety, greater anxiety is related to caregivers displaying more contingency of facial affect [1] with their infants, and less contingency cross-modally [2] When comparing high *vs.* midrange caregiver anxiety, greater anxiety is related to infants displaying less contingency of facial affect with their caregivers [3], and cross-modally [4], except across infant vocal affect and caregiver touch [5] where infants display more contingency	Weak-to-medium relationships (+/-)* [1] β = .03, SE = .01, p = .002 [2] β = -.004, SE = .002, p = .009 [3] β = -.014, SE = .01, p = .027 [4] β = -.32, SE = .14, p = .025 [5] β = .06, SE = .03, p = .028	NA

Ostlund, 2017	Attunement, ~synchrony: ‘emphasises bidirectional influences between a mother and infant, characterises the ability of a dyad to jointly structure biobehavioral development of an infant through repeated experiences across the first months of life’ (p. 15)	Time-series analyses	Caregiver anxiety symptoms are unrelated to physiological attunement	No relationship $\beta < -.01$, SE = .01, $p = .61$	No relationship $\beta = -.02$, SE = .03, $p = .41$
Doba, 2022	Synchrony: ‘temporal concordance between simultaneous or sequential behaviors across a wide range of ... behavioral indicators’ (p. 583)	Cross-recurrence plot & Lempel–Ziv complexity of joint behavioural sequences	Direct effect between caregiver anxiety and caregiver-infant synchrony at six months postpartum	Strong relationship (+) $\beta = .58$, 95% bootstrap CI (0.20, 0.94)	No relationship $\beta = -0.27$, 95 bootstrap CI (−0.61, 0.06)
Kaitz, 2010†	Matching, ~synchrony, ‘extent to which mothers and infants shared joint affective states at the same moment in time (i.e., within the same 1-s interval)’ (p. 142)	Time-series analyses	Anxious caregivers and their infants have more sustained levels of matching states in the pre/post phases of a stressor compared to controls	Weak relationship (+) $F(1, 85) = 3.33$, $p = .071$, $\eta p^2 = .04$	NA
Lotzin, 2015†	Gaze synchrony: ‘the degree of the temporal coordination of behaviors between interaction partners’ (p. 17)	Time-series analyses and cross-correlation functions	Though a relationship between caregiver anxiety and gaze synchrony was found in the initial phase, in a best-fitting model (including caregiver depression, emotion	Medium relationship in initial phase, no relationship in best fitting model (BFM)	No relationship in BFM

			dysregulation, play condition and other demographic variables) anxiety symptoms are unrelated to synchrony	RE estimate = .05, 95% CI -.19, .28	RE estimate = .05, 95% CI (-.25, .36)
Lotzin, 2016	Facial affect synchrony: ‘the temporal coordination of behavior between mother and infant’ (p. 327)	Time-series analyses and cross-correlation functions	Anxious and depressed caregivers demonstrate higher facial affect synchrony with their infants *vs*. caregivers interacting with randomly assigned infants - during both a neutral task [1] and after a stressor [2]	*Anxiety and depression co-occur diagnostically* Medium sized relationship (+) [1] t (134) = 2.20, $p < .030$, $d = .38$ [2] t (134) = 2.96, $p < .004$, $d = .30$	
Holmberg, 2020	Unpredictability: ‘Unpredictability of maternal sensory signals in caregiving behavior’ (p. 5)	Transition probabilities	Caregivers reporting elevated levels of prenatal anxiety symptoms at GWK 24 (but not 14 or 34 GWK, or postnatally) demonstrate higher unpredictability *vs*. caregivers with lower anxiety symptoms	Weak to medium sized relationship (+) $\beta = .197$, $p = .007$	
Granat, 2017[†]	Synchrony: ‘synchrony [is] indicated when mother and infant coordinate their social [behaviour]’ (p. 16)	Conditional probabilities	Anxious caregivers and infants demonstrate higher levels of touch synchrony (by frequency and latency measures) than MDD and CG, and higher levels of gaze synchrony (by duration and latency) than MDD; also longer durations and shorter latencies than CG	Weak to medium sized relationships (+/-) Touch & gaze synchrony[b] Duration (AD *vs*. CG): $r = .20$ Frequency (AD *vs*. CG): $r = .19$ Latency (AD *vs*. CG): $r = -.10$ Duration (AD *vs*. MDD): $r = .38$ Frequency (AD *vs*. MDD): $r = .35$ Latency (AD *vs*. MDD): $r = -.36$	Weak relationships (+/-) Touch & gaze synchrony[b] Duration (MDD *vs*. CG): $r = -.06$ Frequency (MDD *vs*. CG): $r = -.12$ Latency (MDD *vs*. CG): $r = .24$

Smith, 2022†	Synchrony: 'concurrent synchrony ('when A is high, B is high') and sequential synchrony ('changes in A forward-predict changes in B')' (p. 3041)	Time-series analyses and cross-correlation functions	[1] Anxious caregivers show higher physiological concurrent synchrony with their infants *vs*. low anxiety caregivers and infants [2] Anxious caregivers over-responded to small-scale fluctuations in infant stress; greater infant emotion dysregulation [slower return to baseline] was observed among dyads where caregivers over-responded to small-scale fluctuations in infant stress	Medium sized relationship (+) [1] $t(64) = 2.16$, $p = .035$, $r = .26$[a] [2] $\rho = -.33$, $p = .045$	NA
Smith, 2023	Synchrony: 'coordination or covariation between two or more partners' autonomic processes during social contact' (p. 2)	Time-series analyses and permutation-based clustering analyses	[1] When examining the high anxiety group only, caregivers' peaks in their own autonomic arousal tend to cooccur with peaks in infant arousal [2] A relationship was observed between high levels of sustained physiological stress among infants in the high anxiety (but not low anxiety) group after caregivers uttered high-intensity vocalisations	Medium-sized relationship (+) [1] $p = .019$, $r = .28$[a] [2] NA	NA

Notes

In ascending order by infant age. Further information regarding interpretation of correlation coefficients and statistical analyses are available in the Appendix (sections 2-3).
~ = terminology is interchangeable, by definition, with the definition of caregiver-infant synchrony presented in the Introduction.
+/- = direction of relationships, positive effects are signified by '+' and negative effects are signified by '-.'
*Further fine-grain results available in Beebe et al (2011), omitted here for brevity. NA = not available; RE = random effect; GWK = gestation week.
AD = Anxiety Disorder [Group]; MDD = Major Depressive Disorder [Group]; CG = Control Group.
†Included in meta-analysis of caregiver-infant synchrony.
[a]Correlation coefficient calculated from t-test.
[b]Correlation coefficients calculated from means, standard deviations and sample sizes, and averaged across synchrony conditions (touch and gaze) – as such, item level *p* values not shown. See Section 3.4 in main text for further detail. For further information regarding coding and reliability, see Table S3 in the Appendix.

4. Discussion

4.1 Summary of evidence

The present review examined the association between caregiver-infant interaction and perinatal anxiety from a dynamic systems perspective. Of the nine studies reviewed, most reported an association between perinatal anxiety and caregiver-infant synchrony. Synchrony refers to a phenomenon by which dyadic partners match each other's moment-to-moment neural, physiological or behavioural activity (Butler, 2011; Helm et al., 2018; Wass et al., 2020); synchrony is thought to be a core mechanistic factor in caregiver-child anxiety transmission (Perlman et al., 2022). On formal inspection, the meta-analysis of a subset of studies (k = 4) found a significant but small association between perinatal anxiety and caregiver-infant synchrony, indicating that the greater the level of perinatal anxiety, the higher the level of synchronous interactions between caregiver and infant (r = .16). In the narrative synthesis (k = 9), I also noted further patterns of results. Compared to non-anxious caregivers, anxious caregivers and infants were quicker to enter synchronous states (Granat et al., 2017) and took longer to exit them after a stress event (Kaitz et al., 2010). Anxious caregivers and infants also showed mutually high levels of sustained physiological arousal after an intense vocal event, whereas non-anxious caregivers and infants would not (Smith et al., 2023). Finally, the synthesis shed light on the associations between perinatal anxiety and caregiver contingency (i.e., the extent to which the caregiver responds to the infant's cues). Anxious caregivers showed higher levels of responsivity to infant negative cues (Hsu, 2004) and increased reactivity to small-scale fluctuations in infant stress (Smith et al., 2022), compared to non-anxious counterparts. Results suggested that anxious caregivers displayed less consistency in caregiving behaviour (Holmberg et al., 2020) while an investigation of multiple caregiver behaviours indicated a more complex picture, with instances of heightened caregiver contingency in one area (e.g., facial affect), and lowered contingency in another (cross-modally; Beebe et al., 2011).

A small *k* precluded use of meta-regressions to formally inspect co-morbidity, task characteristics, location and system level (physiology *vs.* behaviour) as moderating variables. Results from the narrative synthesis suggested the likelihood of under-responsivity in depressive caregivers *vs.* over-responsivity in anxious caregivers (Granat et al., 2017). In addition, associations between perinatal anxiety and caregiver synchrony/contingency were broadly stronger in studies that examined anxiety without depression (e.g., Doba et al., 2022; Granat et al., 2017) *vs.* studies that looked at co-occurring anxiety and depression (Lotzin et al., 2015, 2016), though it is difficult to disentangle the possibly confounding influence of task characteristics (i.e., neutral condition vs stress induction). In an analysis of all caregivers (anxious and non-anxious), synchronous interactions with infants were observed to be more adult-led following a stressor, compared to a neutral condition (Doba et al., 2022).

Taken together, these results are consistent with existing research demonstrating higher levels of synchrony in high-risk populations (DePasquale, 2020) and heightened reactivity to infant cues in caregivers with elevated anxiety (see, e.g., fMRI studies indicating that caregivers show hyper-reactivity to negative cues in neural circuits associated with regulatory processes, and ERP studies suggesting caregiver hyper-reactivity to neutral infant cues; Yatziv et al., 2021). In addition, the results showing that anxious caregivers display elevated responsivity to minor infant distress are consistent with the existing literature on dyadic sensitivity to context. While mixed, research has shown that parent-child synchrony may be higher in contexts characterised by negative affect (Davis et al., 2018; Woltering et al., 2015). This raises the question of whether anxious caregivers experience an extreme form of this, of being 'always on' instead of 'there when you need me' (Smith et al., 2022; Wass et al., 2024). Finally, the results from the systematic review are coherent with the mid-range model of synchrony, which posits that neither over-coordination (as seen in anxious caregivers) nor under-coordination (as seen in depressed caregivers) in caregiver-infant interaction may be optimal for the child's developing regulatory processes (Jaffe et al., 2001; McFarland et al., 2020).

My finding suggesting that synchronous interactions between infants and anxious caregivers are 'sticky' – i.e., that anxious caregivers and infants enter synchronous states more quickly than depressed caregivers and controls (Granat et al., 2017) and sustain synchronous interactions for longer than non-anxious caregivers (Kaitz et al., 2010; Smith et al., 2023) – is novel. This pattern of results may be understood through the lens of the dynamic systems principle of 'attractors', i.e., stable states in which the dyad tends to settle over time, or states that 'attract' the system from other states (Granic & Patterson, 2006). Clinician-scientists might understand an anxious caregiver-dyad as one that tends to get 'stuck' in a state of high mutual arousal, where the caregiver behaves in a way that stimulates the infant, who then responds in a way that stimulates the caregiver, and so on. This 'mutual high arousal state', once established, may persist for a while. The anxious caregiver's heightened sensitivity to infant distress may explain the speed with which dyads fall into this state.

This review also examined how the relation between caregiver-infant synchrony and perinatal anxiety differs depending on the stage of child development. When infants were younger (< 6 months), weak or no associations were found, whereas when infants were older (>8 months), medium to strong sized relationships were observed. This is broadly consistent with evidence suggesting that synchronous caregiver-infant interaction emerges early and becomes stronger as infants develop greater intentionality and joint attention throughout the first year of life (Feldman, 2012; Harrist & Waugh, 2002). In typical development, synchronous interaction is thought to decline after infancy and middle childhood as children develop greater independence, with moments of synchrony retained only during high arousal events associated with increased demands on affective or socio-cognitive processing (Birk et al., 2022; Lougheed & Hollenstein, 2018; Smith, 2022; Woltering et al., 2015). It is unclear whether this trajectory is altered in the context of perinatal anxiety. It appears that synchronous states between anxious caregiver and infant increase over the first year of life, peak, and then remain at a high level throughout childhood relative to dyads where the caregiver does not have anxiety (Motsan et al., 2021; Roman-Juan et al., 2020). This 'peak, then stay high' trajectory might constrain child autonomy and 'looseness' in interactions, interfering with key mechanisms in the development of self-regulatory processes in young children (Beebe & Lachmann, 2020; Feldman, 2021; Granat et al., 2017). Clinically, it's possible that these early experiences with caregivers could be linked to concepts such as enmeshment (referring to relationships that become dysfunctional when they prevent the individuals involved from separate functioning; Green & Werner, 1996) or co-dependency (referring to an extreme focus of an individual on their partner's mood and behaviour; Lampis et al., 2017). Both include a lack of a clear sense of self. From an outcomes perspective, it is also unclear from this review whether there is any adaptive advantage to increased dyadic synchrony or contingency. For instance, it may be that, through genetic heritability, anxious parents have infants who need greater synchrony within interaction to calm down. Or, it may be that, through being more responsive to their infant, anxious parents may buffer other stressors. At the moment, it is unknown whether this heightened synchrony/contingency in anxious parents has positive or negative implications for later developmental or clinical outcomes.

Finally, this review aimed to review how anxious caregiver-infant interaction relates to infant socio-emotional development, and how this relationship might be affected by wider contextual factors. Initial evidence was found for a pattern whereby higher levels of caregiver reactivity to infants' minor stress signals was related to greater infant emotion dysregulation (Smith et al., 2022). This is consistent with reviews suggesting that, in higher risk populations, heightened caregiver contingency is associated with poorer self-regulation outcomes in children (DePasquale, 2020). Insufficient information precluded formal examination of whether caregiver-interaction represented a mediating variable on the path from perinatal anxiety to child socio-emotional functioning, or whether wider contextual factors (e.g., partner involvement) moderated the association between caregiver anxiety and caregiver-infant interaction. However, caregiver emotion-regulation was found to be an influential variable within multiple studies, both as a moderator (caregiver difficulties with emotion regulation intensified the relation between perinatal anxiety and inconsistent caregiving behaviour; Holmberg et al., 2020) and as part of a mediating relationship (caregiver emotion regulation difficulties associated with heightened maternal anxiety, leading in turn to higher levels of caregiver-infant synchrony; Doba et al., 2022). This is in line with other accounts of high-risk caregiver-child interaction suggesting that optimal coregulation is subserved by the caregiver's ability to dynamically respond to their child's needs and regulate their own physiological reactivity levels (Zhang et al., 2022a). While research on emotion regulation typically focuses on recovery from a negative stressor, evidence from a study of child welfare-involved families suggests that caregiver self-regulation during 'positive' moments of interaction is also necessary; in their dynamic systems account, Zhang and colleagues showed that positive caregiver behaviours led to cardiac arousal increases, which in turn predicted momentary decreases in caregivers' positive verbal engagement (Zhang et al., 2023).

4.2 General conclusions

This review examined the association between caregiver-infant interaction and perinatal anxiety from a dynamic systems perspective. There were three main conclusions. Firstly, there are higher levels of caregiver-infant synchrony when the caregiver has perinatal anxiety, which may be related to overly high caregiver responsivity/contingency. This finding extends our understanding of anxiety-related increases in caregiver-infant synchrony by suggesting its basis in asymmetrical, adult-led interactions (Beebe et al., 2016). Secondly, anxious caregivers and infants' synchronous interactions appear to be 'sticky' – such that caregivers and infants enter synchronous states more quickly and sustain these for longer than non-anxious counterparts - both at the state level and, possibly, over the developmental course. Thirdly, initial evidence suggests that (a) caregiver over-responsivity is related to difficulties in infant self-regulation, and (b) caregiver difficulties with emotion regulation amplify the relation between perinatal anxiety and caregiver-infant synchrony.

4.3 Implications for clinical practice

The present review has several implications for clinical practice. These findings may help with the development of formulation models for perinatal anxiety and caregiver-infant interaction, by highlighting triggers of mutually escalating arousal states for the dyad. Such tools may assist video-feedback based interventions commonly used in the perinatal period (O'Hara et al., 2019) through identifying examples of concrete, bidirectional processes that contribute to coregulation at the biological as well as behavioural level. These may help to further systematise existing interventions based on thematically similar constructs (e.g., attunement/reciprocity, delineated as a process of 'receiving then responding', 'give and take' ; Kennedy et al., 2011). While these interventions show some effectiveness (Newton et al., 2020; O'Hara et al., 2019), perhaps the addition of further cycles of interpersonal relations, including leader-follower and bio-behavioural dynamics, may strengthen them; whether by normalisation (evidence shows how dynamics are generalised), increasing transparency (processes become observable and testable) or reducing variability in administration (processes are more tightly operationalised). Including physiological measures in video-based interventions may also be beneficial for communication and understanding; it may allow for real-time biofeedback to caregivers about both their infant's and their own stress responses, supporting greater awareness and modulation of physiological states.

4.4 Methodological limitations and future studies

This review includes several strengths. Firstly, the review is characterised by methodological rigor with respect to its comprehensive, expansive search strategy, as well as the use of reliability measures throughout the screening, extraction, and quality assessment process. Given that dynamic systems accounts are under-researched compared to other methodological approaches, the broadness of my search terms also allowed for the retrieval of records that included but did not emphasise dynamic quantification. In addition, my analytical approach is multifactorial. I have allowed for both quantitative and qualitative synthesis of the results, allowing me to observe consistency across findings.

The review was also subject to several limitations. Firstly, a small *k* prevented a higher-powered meta-analysis, as well as meta-regressions that would have allowed for formal inspection of the potential influence of moderating variables (e.g., infant age, task characteristics, co-occurring caregiver depression). In addition, power estimates were absent for most eligible studies, and studies were mostly based on convenience or single-site sampling, raising questions regarding the validity and generalisability of results in some cases. Of note, all eligible studies focused on mother-infant relations, precluding an assessment of father-infant or non-binary caregiver-infant relations. Research has lagged behind social changes that have seen – particularly in affluent societies – greater involvement of fathers; this lag has led to a scarcity of biobehavioural studies of father-child interaction that incorporate a time dimension (Feldman, 2023). In addition, developmental research continues to be located within a heteronormative framework, lacking designs that centre the experiences of lesbian, gay, bisexual, transgender, and queer (LGBTQ) caregivers and other diverse family formations (Darwin & Greenfield, 2019, 2022a; see exceptions Abraham et al., 2014; Carone & Lingiardi, 2022). These are especially relevant as caregiver-child dynamics may differ with different children within a family, as choices regarding genetic and gestational parenthood may differ, and as the perinatal period may 'be experienced as beginning earlier', due to planning conception (Darwin & Greenfield, 2022b). Also important to our understanding of caregiver-infant dynamics and the development of emotion regulation is the consideration of cross-cultural differences; the majority of samples in this review were from Western, democratic societies; yet research has suggested that dyads from African, Middle-Eastern and Far-Eastern societies tend to rely on different behavioural modalities during interaction, and may be socialised – as both young children and adults - to regulate their emotions differentially (Diemer et al., 2021; Feldman, 2006).

The results of this review have implications for future research. Firstly, there is a need for more adequately powered analyses and sampling methods that allow for greater generalisability to the wider population. Secondly, research will benefit from longitudinal studies that allow for time series data to be incorporated into structural equation models, enabling path analysis and the identification of mediating relationships over time. Thirdly, research will benefit from a whole family approach, taking into account partner involvement, other children, grandparents, or other members of the system.

Appendix - Supplementary Materials for: Systematic Review

1. Exclusion criteria

The exposure of interest pertained to perinatal anxiety. Subsequently, studies were ineligible if caregivers' mental state was characterised by theoretically or clinically distinct categories (i.e., attachment anxiety, caregiver stress, post-traumatic stress disorder [PTSD], complex PTSD) or stressful life events (i.e., acute child health or feeding issues, neonatal screening, COVID-19, child with disability or colic, assisted conception, perinatal loss). A narrow inclusion criteria for perinatal anxiety was selected to limit heterogeneity in the final sample. Given the review's focus on understanding caregiver-infant interaction with a time dimension, studies were also ineligible if caregiver-infant interaction was measured by global rating scales, summative frequency counts or self/informant-report. Measures of caregiver-infant interaction during pregnancy (e.g., 'caregiver-fetus bonding') were also excluded.

In this review, caregiver-fetus interaction was excluded on the basis of measurement challenges and homogeneity. Prenatal studies often rely on self-reports (Trombetta et al., 2021; Wittkowski et al., 2020), introducing potential biases and often representing a time invariant measure; in contrast, postnatal interactions can be more easily directly and continuously observed. Excluding caregiver-fetus interactions thus increased the likely reliability of data, as well as the likelihood of retrieving dynamic systems accounts. It is also worth highlighting that theoretical constructs of caregiver-child interaction between the prenatal and postnatal period differ, with prenatal constructs emphasising caregiver affective appraisal of pregnancy, and postnatal theories focusing on the impact of infant characteristics and the interplay of this with caregiver regulatory processes (DiPietro et al., 2021). Excluding caregiver-fetus interaction while including caregiver-infant interaction thus promoted measurement homogeneity and avoided conflating conceptually different constructs.

2. Information regarding statistical analyses

The following represents a summary of the statistical analyses outlined in Table 2, which may be of interest to those unfamiliar with time variant methodologies. Of note, I use the terms 'we' and 'us' here as impersonal collective pronouns, rather than to refer to any specific group of researchers.

Conditional probabilities allow us to identify how likely a behaviour in one individual might occur given preceding behaviour from another individual. Similarly, *transitional probabilities* help us to identify, over time, the likelihood of a state or behaviour following another. *Time series analyses* may describe the way one or more individuals' behaviour or physiological activity is structured over time. When we look at a time series of data, this allows us to see whether activity is periodic and predictable, or whether it's more variable. We can also compare time series of data, looking at whether the series appear to match one another, or where one appears to control or influence the other (sometimes with bidirectional influences). One way this can be looked at is by using a *cross correlation function*. This allows us to look at the question, ‘when partner A is high in a certain activity, is partner B also high in this activity?’ To do this, we measure how similar two time series are as a function of displacing one relative to the other. We do this by incrementally shifting one time series back by a ‘lag’ and repeatedly calculating correlations between the two signals. A *permutation based clustering test* helps us to understand, when looking at data with a time dimension, the difference between real trends and random fluctuations. Permutation based clustering tests are largely based on techniques akin to bootstrapping as a means of determining the statistical significance of patterns observed within data.

Cross-recurrence plots are a type of graph that allow for the analysis and visualisation of behavioural or physiological patterns that recur across 2+ time series datasets. The *Lempel-Ziv complexity measure* quantifies how complex and variable the data from two sequences of behaviour might be. This can allow researchers to look at questions around how predictable behaviour from two individuals might be, as well as how frequently new patterns emerge throughout the sequence.

3. Interpreting Correlation Coefficients

The below rubric (Viechtbauer, 2021) is presented to aid the interpretation of correlation coefficients presented in Table 2.

Value of r	*Interpretation*
r = –1.0	perfect decreasing relationship
r = –0.5	strong decreasing relationship
r = –0.3	medium decreasing relationship
r = –0.1	weak decreasing relationship
r = 0.0	no relationship/effect
r = +0.1	weak increasing relationship
r = +0.3	medium increasing relationship
r = +0.5	strong increasing relationship
r = +1.0	perfect increasing relationship

Table S1. Quality assessment matrix

Study	1	2	3	4	5	6	7	8	9	10	11
Beebe, 2011	N	N	Y	Y	N	Y	N	N	Y	Y	N
Doba, 2022	N	N	N	N	N	Y	N	N	Y	Y	Y
Granat, 2017	N	Y	N	Y	N	Y	N	Y	Y	Y	N
Holmberg, 2020	Y	Y	N	N	Y	Y	N	N	N	Y	N
Hsu, 2004	N	N	Y	N	N	Y	N	N	Y	N	Y
Kaitz, 2010	N	N	Y	Y	Y	Y	N	Y	Y	Y	N
Lotzin, 2015, 2016	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y
Ostlund, 2017	N	N	N	Y	N	Y	N	N	N	Y	N
Smith, 2022, 2023	N	N	N	Y	Y	Y	N	N	Y	N	Y

Note. Item explanations: 1: Has the study defined eligibility and exclusion criteria for the sample, including time period (dates) and location(s) of recruitment and assessment? 2: Is the sample representative of a defined population (i.e., is the sample based on cohorts recruited from the general population, from multi-site studies, and large databases *vs*., e.g., single-site convenience sample studies, or those with insufficient detail to establish generalisability?) 3: Is a power calculation for the sample provided? 4: Does the study meet satisfactory participation rates (< 39%)? 5: Does the study mention missing data and account for how they were treated in the analysis (studies that remove incomplete data from the outset and do not include it in the total *N* are considered meeting the criteria for addressing missing data)? 6: Does the study use a validated instrument for the assessment of the exposure? 7: Does the study use a validated instrument for the assessment of the outcome? 8: Does the study use objective methods to assess the exposure (self-report is considered subjective, diagnostic interview is considered objective)? 9: Does the study use multiple methods to assess the outcome? 10: Were key potential confounding variables measured / adjusted for statistically in the analyses? 11: Does the study report detailed demographic data for caregivers and children included in the study? Y = Yes; N = No.

Table S2. Reasons for excluding records screened at full text

Original ti ab classification	Title	Author(s)	Year	Reason for Exclusion
Maybe	Antenatal prediction of mother-infant difficulties	Adler et al.	1991	Interaction measure is time invariant
Maybe	Maternal overcontrol and child anxiety: The mediating role of perceived competence	Affrunti et al.	2012	Child age too old
Maybe	How do parents' depression and anxiety, and infants' negative temperament relate to parent-infant face-to-face interactions?	Aktar et al.	2017	Interaction measure is time invariant
Maybe	Parental expressions of anxiety and child temperament in toddlerhood jointly predict preschoolers' avoidance of novelty	Aktar et al.	2018	Interaction measure is time invariant
Maybe	Maternal Prenatal Anxiety and Children's Externalizing and Internalizing Behavioral Problems: The Moderating Roles of Maternal-Child Attachment Security and Child Sex	Ali et al.	2020	Interaction measure is time invariant
Maybe	Specifying the neurobiological basis of human attachment: Brain, hormones, and behavior in synchronous and intrusive mothers	Atzil et al.	2011	Interaction measure is time invariant
Maybe	Anxiety as a potential factor affecting maternal attachment	Avant et al.	1981	Interaction measure is time invariant
Maybe	Parent-child interactions with anxious children and with their siblings: An observational study	Barrett et al.	2005	1. Child age too old 2. Interaction measure is time invariant
Maybe	Maternal control behavior and locus of control: examining mechanisms in the relation between maternal anxiety disorders and anxiety symptomatology in children	Becker et al.	2010	Child age too old

Maybe	Mother-and father-infant-relationships in infants referred to a specialised interdisciplinary service for infants and toddlers	Bolten et al.	2014	Conference abstract
Maybe	An exploration of the relationships among postpartum depression, anxiety, maternal sensitivity, parenting stress, and infant development	Bonwell	2013	Dissertation
Maybe	Maternal perinatal mental health: Associations with bonding, mindfulness, and self-criticism at 18 months' postpartum	Brassel et al.	2020	Interaction measure is self-report
Maybe	Do parental behaviours predict anxiety symptom levels? A 3 year follow up	Breinholst et al.	2019	Child age too old
Maybe	Early inherited risk for anxiety moderates the association between fathers' child-centered parenting and early social inhibition	Brooker et al.	2016	Interaction measure is time invariant
Maybe	The association between infants' attention control and social inhibition is moderated by genetic and environmental risk for anxiety	Brooker et al.	2011	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Depression and Anxiety in the Postnatal Period: An Examination of Infants' Home Language Environment, Vocalizations, and Expressive Language Abilities	Brookman et al.	2020	Interaction measure is time invariant
Maybe	An investigation into the impact of postnatal obsessive-compulsive disorder (OCD)	Challacombe et al.	2013	Conference abstract
Maybe	Postpartum maternal separation anxiety, overprotective parenting, and children's social-emotional well-being: longitudinal evidence from an Australian cohort	Cooklin et al.	2013	Interaction measure is self-report
Maybe	The relationship among parental separation anxiety, infant temperament and parent-infant interaction during separation: A longitudinal study	Curry	1991	Dissertation

Maybe	Consistency of maternal attitudes and personality from pregnancy to eight months following childbirth	Davids et al.	1970	1. Interaction measure is self-report 2. Interaction measure is time invariant
Maybe	Continuous feelings of love? The parental bond from pregnancy to toddlerhood	de Cock et al.	2016	Book chapter
Maybe	Transmission of social anxiety from mother to infant: An experimental study using a social referencing paradigm	de Rosnay et al.	2006	Interaction measure is time invariant
Maybe	Mother-child attachment in clinically-referred preschool children: Association with variables related to mother's own psychological functioning	Delbarre et al.	2020	Article not written in English
Maybe	Mother-child interaction: Implications of chronic maternal anxiety and depression	Dib et al.	2019	Interaction measure is time invariant
Maybe	Maternal covert and overt behavior as a function of anxiety and stress during mother-child interactions	Dibari-Lodico	2007	Dissertation
Maybe	Predicting social-emotional and cognitive development at 24 months: The impact of postnatal maternal anxiety and depressive symptoms, and mother-child relationships	Donahue	2015	Dissertation
Maybe	Parenting practices of anxious and nonanxious mothers: A multi-method, multi-informant approach	Drake et al.	2011	1. Child age too old 2. Interaction measure is time invariant
Maybe	Neonatal risk, maternal sensitive-responsiveness and infants' joint attention: Moderation by stressful contexts	Egotubov et al.	2020	Interaction measure is time invariant
Maybe	Temporal relations in daily-reported maternal mood and disruptive child behavior.	Elgar et al.	2004	Child age too old

Maybe	The relationship of prenatal maternal anxiety to infant behavior and mother-infant interaction during the first six months of life	Farber et al.	1981	Interaction measure is time invariant
Maybe	Maternal versus child risk and the development of parent - Child and family relationships in five high-risk populations	Feldman	2007	Interaction measure is time invariant
Maybe	Maternal Depression and Anxiety Across the Postpartum Year and Infant Social Engagement, Fear Regulation, and Stress Reactivity	Feldman et al.	2009	Interaction measure is time invariant
Maybe	Change in mother-infant interactive behavior: Relations to change in the mother, the infant, and the social context	Feldman et al.	1997	Interaction measure is time invariant
Maybe	Anxiety and anger effects on depressed mother-infant spontaneous and imitative interactions	Field et al.	2005	Interaction measure is time invariant
Maybe	Anxiety, depression, and emotional involvement with the child during pregnancy	Figueiredo et al.	2007	Article not written in English
Maybe	Mother's anxiety and depression during the third pregnancy trimester and neonate's mother versus stranger's face/voice visual preference.	Figueiredo et al.	2010	Interaction measure is time invariant
Maybe	Mothers' neural response to valenced infant interactions predicts postpartum depression and anxiety	Finnegan et al.	2021	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Antenatal maternal anxiety, maternal sensitivity and toddlers' behavioral problems: An investigation of possible pathways	Frigerio & Nazzari	2021	Interaction measure is time invariant
Maybe	Characteristics and clinical consequences of prenatal depression. Main results of a prospective case-control study on perinatal depression from pregnancy to one year-old infant	Gerardin et al.	2012	Article not written in English

Maybe	Paternal Anxiety in Relation to Toddler Anxiety: The Mediating Role of Maternal Behavior	Gibler et al.	2018	Interaction measure is self-report
Maybe	Maternal sensitivity moderates the impact of prenatal anxiety disorder on infant mental development	Grant et al.	2010	Interaction measure is time invariant
Maybe	Clustering phenotype trajectories with genotype covariates	Greenlaw et al.	2016	Conference abstract
Maybe	Severity of anxiety moderates the association between neural circuits and maternal behaviors in the postpartum period	Guo et al.	2018	Interaction measure is time invariant
Maybe	How maternal pre- and postnatal symptoms of depression and anxiety affect early mother-infant interaction?	Hakanen et al.	2019	Interaction measure is time invariant
Maybe	Interparental conflict, parent psychopathology, hostile parenting, and child antisocial behavior: Examining the role of maternal versus paternal influences using a novel genetically sensitive research design	Harold et al.	2012	Child age too old
Maybe	Neonatal auditory evoked responses are related to perinatal maternal anxiety	Harvison et al.	2009	1. Interaction measure is time invariant 2. No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Association between parental emotional symptoms and child antisocial behaviour: What is specific and is it mediated by parenting?	Hautmann et al.	2015	1. Child age too old 2. Interaction measure is time invariant
Maybe	Depression and anxiety as developmental precursors to adolescent mothers' attributions of infant agency	Hipwell et al.	2015	Conference abstract
Maybe	Predicting adolescent postpartum caregiving from trajectories of depression and anxiety prior to childbirth: A 5-year prospective study	Hipwell et al.	2016	Interaction measure is time invariant

Maybe	Separation anxiety in first-time mothers: Infant behavioral reactivity and maternal parenting self-efficacy as contributors	Hsu et al.	2008	Interaction measure is time invariant
Maybe	Psychopathological and Psychosocial Risk Profile, Styles of Interaction and Mentalization of Adolescent and Young Mother-Infant Dyads	Ierardi et al.	2022	Interaction measure is time invariant
Maybe	Parental embodied mentalizing: Associations with maternal depression, anxiety, verbal mentalizing, and maternal styles of interaction	Ierardi et al.	2022	Interaction measure is time invariant
Maybe	Maternal and paternal depression and anxiety: their relationship with mother-infant interactions at 3 months	Ierardi et al.	2019	Interaction measure is time invariant
Maybe	Maternal Parasympathetic Regulation During Dyadic Stress: Associations With Emotional Availability, Maternal Depressive and Anxiety Symptoms, and Infant Distress	Jamieson et al.	2021	Conference abstract
Maybe	Breastfeeding and maternal sensitivity predict early infant temperament	Jonas et al.	2015	Interaction measure is time invariant
Maybe	Maternal respiratory sinus arrhythmia contextualizes the relation between maternal anxiety and overprotective parenting	Jones et al.	2022	Child age too old
Maybe	The Relation between Specific Parenting Behaviors and Toddlers' Early Anxious Behaviors is Moderated by Toddler Cortisol Reactivity	Kalomiris et al.	2019	Interaction measure is self-report
Maybe	Impact of maternal attachment on infant development at one year of age: Results from the otis antidepressants in pregnancy study	Karam et al.	2012	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Maternal pre- and postnatal anxiety symptoms and infant attention disengagement from emotional faces.	Kataja et al.	2019	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction

Maybe	Anxiety and defensiveness as predictors of maternal child-centrism.	Kestler-Peleg et al.	2018	1. Child age too old 2. Interaction measure is self-report
Maybe	Transactional relations between maternal anxiety and toddler anxiety risk through toddler-solicited comforting behavior	Kiel et al.	2021	Interaction measure is time invariant
Maybe	Construct Validation for Toddler-Solicited Maternal Comforting Behavior as Relevant to Family Accommodation and Child Anxiety Risk	Kiel & Baumgartner	2023	Child age too old
Maybe	Temperament variation in sensitivity to parenting: Predicting changes in depression and anxiety	Kiff et al.	2011	1. Child age too old 2. Interaction measure is time invariant
Maybe	Mothers' frontal EEG asymmetry in response to infant emotion states and mother-infant emotional availability, emotional experience, and internalizing symptoms	Killeen & Teti	2012	Interaction measure is time invariant
Maybe	Associations of partnership quality and father-to-child attachment during the peripartum period. A prospective-longitudinal study in expectant fathers	Knappe et al.	2021	Interaction measure is self-report
Maybe	Associations of partnership quality and father-to-child attachment during the peripartum period. A prospective-longitudinal study in expectant father	Knappe et al.	2022	Interaction measure is self-report
Maybe	Adult separation anxiety and unsettled infant behavior: Associations with adverse parenting during childhood and insecure adult attachment	Kohlhoff et al.	2015	Interaction measure is self-report
Maybe	Postnatal depression, maternal bonding failure, and negative attitudes towards pregnancy: A longitudinal study of pregnant women in Japan	Kokubu et al.	2012	Interaction measure is self-report

Maybe	Maternal prenatal mood problems and lower maternal emotional availability associated with lower quality of child's emotional availability and higher negative affect during still-face procedure	Korja et al.	2021	Interaction measure is time invariant
Maybe	Parents' psychological well-being and parental self-efficacy in relation to the family's triadic interaction	Korja et al.	2015	Interaction measure is time invariant
Maybe	The relationship between parental depression and children's depression in a latino sample	Laracuenta	2006	Dissertation
Maybe	The role of maternal anxiety disorder subtype, parenting and infant stable temperamental inhibition in child anxiety: A prospective longitudinal study	Lawrence et al.	2020	Interaction measure is time invariant
Maybe	Challenges related to migration and child attachment: A pilot study with South Asian immigrant mother-child dyads	Lecompte et al.	2018	1. Child age too old 2. Interaction measure is time invariant
Maybe	Determinants of Child Attachment in the Years Postpartum in a High-Risk Sample of Immigrant Women	Lecompte & Rousseau	2018	Interaction measure is time invariant
Maybe	The effects of adolescent mothers' mental health, parenting behavior, social support, and child temperament on child development.	Lee	2013	Dissertation
Maybe	Effect of maternal depression and anxiety on mother's perception of child and the protective role of social support	Lefkovics et al.	2018	Interaction measure is self-report
Maybe	Maternal anxiety symptoms associated with increased behavioral synchrony in the early postnatal period.	Lemus et al.	2022	Interaction measure is time invariant
Maybe	Predictors of parent and child behaviors during daily separations and reunions at daycare.	Livesey	1997	Dissertation

Maybe	Paternal history of depression or anxiety disorder and infant-father attachment.	Lucassen et al.	2018	Interaction measure is time invariant
Maybe	Prospective study of maternal behavior in the neonatal period: a pilot study.	Lugt-Tappeser et al.	1994	Article not written in English
Maybe	A prospective study on maternal behavior during the neonatal period: A pilot study.	Lugt-Tappeser et al.	1994	Duplicate
Maybe	Fathers' postnatal depressive and anxiety symptoms: an exploration of links with paternal, maternal, infant and family factors.	Luoma et al.	2013	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Second-by-second maternal management of 4-month infant gaze aversion: A quantification of "good enough" mothering.	Lupi	2009	Dissertation
Maybe	Antenatal determinants of parental attachment and parenting alliance: how do mothers and fathers differ?	Luz et al.	2017	Interaction measure is self-report
Maybe	Do Maternal Parenting Behaviors Indirectly Link Toddler Dysregulated Fear and Child Anxiety Symptoms?	Maag et al.	2021	Child age too old
Maybe	The parental bonds of adolescent girls and next-generation maternal-infant bonding: findings from the Victorian Intergenerational Health Cohort Study.	Macdonald et al.	2018	Interaction measure is self-report
Maybe	Anger and parent-to-child aggression in mood and anxiety disorders.	Mammen et al.	2000	1. Child age too old 2. Interaction measure is self-report
Maybe	Shared pleasure in early mother-infant interaction: Predicting lower levels of emotional and behavioral problems in the child and protecting against the influence of parental psychopathology	Mantymaa et al.	2015	Interaction measure is time invariant

Maybe	Maternal anxiety disorders prior to conception, psychopathology during pregnancy and early infants' development: a prospective-longitudinal study.	Martini et al.	2013	Interaction measure is time invariant
Maybe	Predicting maternal reactivity/sensitivity: The role of infant emotionality, maternal depressiveness/anxiety, and social support	Mertesacker et al.	2004	Interaction measure is time invariant
Maybe	Concurrent and Predictive Associations Between Infants' and Toddlers' Fearful Temperament, Coparenting, and Parental Anxiety Disorders	Metz et al.	2018	1. Interaction measure is self-report 2. No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Fathers' versus mothers' social referencing signals in relation to infant anxiety and avoidance: a visual cliff experiment.	Moller et al.	2014	Interaction measure is time invariant
Maybe	Don't worry, be (moderately) happy: Mothers' anxiety and positivity during pregnancy independently predict lower mother-infant synchrony.	Moore et al.	2016	Interaction measure is time invariant
Maybe	Behavioral Inhibition in the Second Year of Life Is Predicted by Prenatal Maternal Anxiety, Overprotective Parenting and Infant Temperament in Early Infancy.	Mudra et al.	2022	Interaction measure is self-report
Maybe	The effects of maternal social phobia on mother-infant interactions and infant social responsiveness.	Murray et al.	2007	Interaction measure is time invariant
Maybe	Intergenerational transmission of social anxiety: The role of social referencing processes in infancy.	Murray et al.	2008	Interaction measure is time invariant
Maybe	Parental Sensitivity and Responsiveness as Mediators Between Postpartum Mental Health and Bonding in Mothers and Fathers.	Nakic Rados	2021	Interaction measure is self-report

Maybe	The association between prenatal maternal anxiety disorders and postpartum perceived and observed mother-infant relationship quality.	Nath et al.	2019	Interaction measure is time invariant
Maybe	Transactions between child social wariness and observed structured parenting: Evidence from a prospective adoption study	Natsuaki et al.	2013	Interaction measure is time invariant
Maybe	Pathways from a worried mother to a fearful child: The roles of maternal anxiety and responsive environment.	Natsuaki et al.	2010	Conference abstract
Maybe	Maternal caregiving moderates the impact of antenatal maternal cortisol on infant stress regulation.	Nazzari et al.	2022	Interaction measure is time invariant
Maybe	Interactions between mothers and infants: Impact of maternal anxiety.	Nicol-Harper et al.	2007	Interaction measure is time invariant
Maybe	Maternal postnatal psychiatric symptoms and infant temperament affect early mother-infant bonding.	Nolvi et al.	2016	Interaction measure is self-report
Maybe	The relationship of maternal perception and maternal behavior: A study of normal mothers and their infants.	Nover et al.	1984	Interaction measure is time invariant
Maybe	Maternal psychopathology and stress: Fetal, infant, and toddler outcomes	O’Hara et al.	2011	Conference abstract
Maybe	Sensitive and harsh parenting of infants: Associations with maternal depression, generalized anxiety, and empathic concern.	Ojo et al.	2021	Interaction measure is time invariant
Maybe	Baby's mind in mind: Prenatal parental capacity to mentalise about the baby. Data from the FinnBrain birth cohort study.	Pajulo et al.	2011	Conference abstract
Maybe	The impact of parents' mental health on parent-infant interaction: A prospective study.	Parfitt et al.	2015	Interaction measure is time invariant

Maybe	Mothers with depressive symptoms: Cross-situational consistency and temporal stability of their parenting behavior.	Pauli-Pott	2008	Interaction measure is time invariant
Maybe	Predicting the development of infant emotionality from maternal characteristics	Pauli-Pott et al.	2004	Interaction measure is time invariant
Maybe	Mother-infant affective concordance is associated with EEG correlates of anxiety risk in the first two years of life	Perez-Edgar	2021	Conference abstract
Maybe	Maternal depression and mother-child oxytocin synchrony in youth with anxiety disorders.	Polack et al.	2021	Child age too old
Maybe	Postpartum mental health and bonding in mothers and fathers: The role of parental sensitivity.	Rados	2022	Conference abstract
Maybe	Initial Evidence for Symptoms of Postpartum Parent-Infant Relationship Obsessive Compulsive Disorder (PI-ROCD) and Associated Risk for Perturbed Maternal Behavior and Infant Social Disengagement From Mother.	Ratzoni et al.	2021	Interaction measure is time invariant
Maybe	Trajectories of clinical and parenting outcomes following admission to an inpatient mother-baby unit.	Reilly et al.	2019	Interaction measure is self-report
Maybe	Positive maternal interaction behavior moderates the relation between maternal anxiety and infant regulatory problems	Richter et al.	2013	Interaction measure is time invariant
Maybe	Longitudinal relations between child evaluative concerns and social anxiety: Does seeking perfectionism predict increases in social anxiety?	Risley	2022	Dissertation
Maybe	Mother-infant emotion regulation at three months: The role of maternal anxiety, depression and parenting stress.	Riva Crugnola et al.	2016	Interaction measure is time invariant

Maybe	Early styles of interaction in mother-twin infant dyads and maternal mental health.	Riva Crugnola et al.	2020	Interaction measure is time invariant
Maybe	Association between independent reports of maternal parenting stress and children's internalizing symptomatology.	Rodriguez et al.	2011	Child age too old
Maybe	Maternal-fetal attachment in pregnant Italian women: multidimensional influences and the association with maternal caregiving in the infant's first year of life	Sacchi et al.	2021	Interaction measure is time invariant
Maybe	Maternal symptoms of depression and anxiety during the postpartum period moderate infants' neural response to emotional faces of their mother and of female strangers.	Sandre et al.	2022	Interaction measure is time invariant
Maybe	Mothers of anxious/ambivalent infants: Maternal characteristics and child-care context.	Scher et al.	2000	Interaction measure is time invariant
Maybe	Repetitive Negative Thinking and Impaired Mother-Infant Bonding: A Longitudinal Study.	Schmidt et al.	2017	Interaction measure is self-report
Maybe	Maternal anxiety, risk factors and parenting in the first post-natal year.	Seymour et al.	2015	Interaction measure is self-report
Maybe	Maternal antenatal anxiety, postnatal stroking and emotional problems in children: outcomes predicted from pre- and postnatal programming hypotheses.	Sharp et al.	2015	Interaction measure is self-report
Maybe	A path model examination: maternal anxiety and parenting mediate the association between maternal adverse childhood experiences and children's internalizing behaviors.	Shih et al.	2021	1. Child age too old 2. Interaction measure is time invariant
Maybe	Maternal cognitions and mother-infant interaction in postnatal depression and generalized anxiety disorder.	Stein et al.	2012	Interaction measure is time invariant

Maybe	Parental brain function and structure: Effects of early life experience, contemporaneous breastfeeding, correlations with behavior and changes in the early postpartum	Swain et al.	2010	Conference abstract
Maybe	Emotion circuits in the parental brain vary with gender, correlate with mood, and predict behavior	Swain et al.	2010	Conference abstract
Maybe	Emotions and behavior affect the brain according to parenting, gender, delivery and breastfeeding	Swain et al.	2011	Conference abstract
Maybe	Infant face interest is associated with voice information and maternal psychological health	Taylor et al.	2014	1. Interaction measure is self-report 2. No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Predictors of positive and negative parenting behaviours: Evidence from the ALSPAC cohort	Thomson et al.	2014	Interaction measure is time invariant
Maybe	Maternal prenatal stress and cortisol reactivity to stressors in human infants	Tollenaar et al.	2011	Interaction measure is time invariant
Maybe	Variable- and person-centered approaches to affect-biased attention in infancy reveal unique relations with infant negative affect and maternal anxiety	Vallorani et al.	2021	No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	The role of perceived parenting in familial aggregation of anxiety disorders in children	van Gastel et al.	2009	Child age too old

Maybe	The relationship of prenatal maternal depression or anxiety to maternal caregiving behavior and infant behavior self-regulation during infant heel lance: An ethological time-based study of behavior	Warnock et al.	2016	Interaction measure is time invariant
Maybe	Maternal age is a significant predictor of infant temperament: The contribution of prenatal and postpartum factors on infant reactivity	Werner et al.	2011	Conference abstract
Maybe	Characterizing interactions between anxious mothers and their children	Whaley et al.	1999	1. Child age too old 2. Interaction measure is time invariant
Maybe	The association between parental bonding and obsessive compulsive disorder in offspring at high familial risk	Wilcox et al.	2008	1. Child age too old 2. No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction
Maybe	Factors associated with poor father-to-infant attachment at 6 months postpartum: A community study in Victoria, Australia	Wynter et al.	2020	Conference abstract
Maybe	Child Negative Emotionality and Parental Harsh Discipline in Chinese Preschoolers: The Different Mediating Roles of Maternal and Paternal Anxiety.	Xing et al.	2017	Child age too old
Maybe	Children with co-occurring anxiety and externalizing disorders: family risks and implications for competence.	Yoo et al.	2009	1. Child age too old 2. No direct interaction measure, e.g., video for experimental stimuli or parent-to-parent interaction

Maybe	Effects of personality characteristics, child-rearing history and anxiety regarding separation on attachment.	Yurik	1996	Dissertation
Maybe	Mothers' alexithymia, depression and anxiety levels and their association with the quality of mother-infant relationship: a preliminary study.	Yurumez et al.	2014	1. Child age too old 2. Interaction measure is time invariant

Table S3. Coding and reliability information for included studies

	Coding	**Reliability**
Hsu, 2004	Continuous, moment-to-moment coding of infant behavioural regulation to pacifier/dummy withdrawal (including hand-to-mouth movements) and the intensity of negative vocalisations and facial expressions.	Reliability checks were conducted on 13% of sessions, with correlations for latency and hand-to-mouth movements at .99 and 1.0, respectively. κ values for intensity ratings of distress were .97.
Beebe, 2011	The first 2.5 minutes coded of mother-infant play were coded on a 1-second time base with coders blind to anxiety status. Behaviours included gaze, facial affect, vocal affect, spatial orientation, head orientation, touch, and dyadic interaction (chase and dodge).	Coding was performed by doctoral students. Reliability was assessed on 30 dyads, with κ values ranging from .68 to .90 for different behaviours.
Ostlund, 2017	Measurement of physiological responses (RSA reactivity) through heart rate and respiration data. Grouped RSA values into 5-second epochs.	Reliability details not available.
Doba, 2022	Video recordings were coded on a 3-second time base across maternal and infant dimensions. Maternal behaviours included verbal (silence, reflective verbalisation, vocalisations), motor (no movement, touch, movement without physical contact), and gaze (toward infant, away). Infant behaviours included vocal (positive/neutral, negative), motor, and gaze. Additionally, behavioural involvement and distress levels were coded.	Reliability assessed on 20% of recordings. κ coefficients ranged from .69 to .99 for different behaviours.
Kaitz, 2010	Continuous coding of mother-infant interactions on a 1-second time base using the Infant and Caregiver Engagement Manual, focusing on phases of affective engagement.	Reliability κ values from double-coding for time-series ranged from .76 to .84.
Lotzin, 2015, 2016	Coding of gaze and other behaviours during Still-Face paradigm using the Maternal Regulatory Scoring System and the Infant Regulatory Scoring System (Tronick & Weinberg, 1990), including gaze direction, caregiving behaviour, and vocalisations. Gaze	Two raters were trained to κ ≥ .80. Inter-rater reliability was assessed for 33.8% of time series, with κ values ranging from .95 to .97 for different conditions.

	behaviours were categorised into gaze at partner, object, away, and unscorable. Micro-coded at 25 times per second (every 40 ms).	
Holmberg, 2020	Continuous coding of maternal sensory signals (auditory, visual, tactile) during play, including speech, object presentation, and touch.	Interrater agreement was 86.1%, assessed by double-scoring 10% of the tapes.
Granat, 2017	Microanalysis of mother-infant synchrony using the Synchrony Coding Scheme (CIB manual; Feldman, 1998), focusing on gaze, affect, vocalisation, and touch for both mothers and infants. Coding included durations, frequencies, and latencies.	Reliability was assessed by comparing the coding of 20 interactions, achieving an average agreement of 91.11% (κ = .88).
Smith, 2022, 2023	Autonomic data (HR and HRV) down-sampled into 1-minute epochs, cross-validated by recording using home-use and lab-based devices. Five-second snapshots every 60 seconds for vocal coding. Vocal intensity categorised as low, medium, or high.	For home-use and lab-based device cross-validation, high reliability was observed both for heart rate ($\rho = 0.57$, $p < 0.001$) and heart rate variability ($\rho = 0.70$, $p = 0.01$). For vocalisations, 24% of vocal samples were double-coded; κ for inter-rater reliability = .60.

Notes
κ = Cohen's kappa
Given the specific research questions, most of the above studies eschewed standardised coding schemes in favour of custom frame-by-frame or continuous coding systems that were tailored to the specific behaviours or physiological measures under investigation. This approach allows for greater specificity and relevance to individual study aims but may reduce comparability across the studies.

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CHAPTER 2 – Main Empirical Project

A dynamic systems account of how perinatal anxiety impacts caregiver-infant synchrony

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Abstract

To develop greater understanding of how perinatal anxiety relates to child socio-emotional development, this study presents a model of the dynamic processes involved in caregiving where the adult has anxiety. Naturalistic data were collected by miniaturised ECG and audio-recording devices worn by 57 mothers and their 5-10 month old infants at home for the day. Using time series data (mean data available per dyad = 396.6 60-second epochs), I examined the temporal relations between caregiver and infant physiology and caregiver vocal behaviour, and how this relates to caregiver anxiety level. The pattern of results was partially consistent with the hypothesised elevation in caregiver-infant synchrony between more anxious caregivers and their infants. Exploratory analyses also revealed associations between caregiver anxiety level, intrusive vocal caregiver behaviour, and both caregiver and infant reactivity. Findings shed light on how anxious caregiving manifests in infancy, allowing us to identify active triggers of coordinating and escalating physiological arousal within the caregiver-infant dyad. This is discussed with respect to implications for future clinical research and practice, including a consideration of how wearable technology could promote accessibility of parent-infant relationship assessments and augment existing parent-infant interventions.

1. Introduction

1.1 Perinatal anxiety and child socio-emotional development

Perinatal anxiety impacts caregiver wellbeing both prenatally and postnatally, and significantly affects caregiver-child relations. Perinatal anxiety is characterised by negative cognitive biases, heightened physiological arousal, and behavioural avoidance (Harrison & Alderdice, 2020), and is a common condition; it has a diagnostic prevalence of approximately 15% globally (20% in the UK; Ayers et al., 2024), rising to 25% of women endorsing clinically significant symptoms when based on self-reported symptoms (Dennis et al., 2017; Nielsen-Scott et al., 2022). Untreated perinatal anxiety is associated with moderate to severe outcomes: tokophobia, coping difficulties, and increased suicidality in caregivers (Demšar et al., 2018; Farias et al., 2013; George et al., 2013), as well as higher odds of preterm birth, low birth weight, and birth complications (Dowse et al., 2020; Grigoriadis et al., 2018; Hoyer et al., 2020). Children are also affected: toddlers of caregivers who experienced anxiety in the perinatal period have significantly higher odds of experiencing difficulties with socio-emotional functioning (e.g., self-regulation, social interaction; Polte et al., 2019), and there is a twofold risk of child mental health conditions in offspring of caregivers with anxiety in the perinatal period (child ages 4-13 years old; O'Donnell et al., 2014; though see below for possible genetic confounding).

For the caregiver-infant relationship, perinatal anxiety manifests through altered interactions. Anxious caregivers show less responsivity to infant activities and affective cues (Ierardi et al., 2019), less consistency in caregiving behaviour (Holmberg et al., 2020), more stimulating, positive behaviours[9] (Granat et al., 2017; Murray et al., 2008), and more overinvolved and autonomy-limiting behaviour (Hakanen et al., 2019). Research also indicates that anxious caregivers are more vigilant to stressors; they show higher reactivity to small-scale fluctuations in infant distress compared to non-anxious caregivers (Smith et al., 2022). Under heightened stress, anxious caregivers are also more likely to speak to their infants in bursts; alternating between periods of rapid articulation and sudden pauses (Smith et al., 2023). These interaction dynamics have been linked to the intergenerational transmission of anxiety and stress states between caregivers and infants, rooted in systemic developmental theories that view emotion regulation as a product of transactional, mutual processes that occur between the dyad (i.e., the 'transactional model of socio-emotional development' and 'mutual regulation model'; Sameroff & Fiese, 1990; Tronick et al., 1998; Tronick, 1989).

1.2 Mechanisms of caregiver-to-child anxiety transmission

Diverse mechanisms are thought to explain the intergenerational transmission of anxiety, defined as the development of anxiety in children as a result of caregiver characteristics and caregiver-child interactions (Aktar et al., 2019; de Vente et al., 2020; Smith, 2022). The fetal programming hypothesis posits that children are at increased likelihood of developing anxiety due to changes in utero that are associated with anxiety characteristics in the gestational parent (e.g., changes in placenta function and fetal hypothalamic-pituitary-adrenal axis function; McLean et al., 2020; O'Donnell & Meaney, 2017; Van den Bergh et al., 2020). Critiques of the fetal programming hypothesis include its modest effect sizes, its inability to explain why prenatal stress has little effect on most children and why those who are affected are affected in diverse ways; there are also issues with inferring causality due to the largely correlational nature of evidence (Davis et al., 2018; O'Donnell & Meaney, 2017). Related to the fetal programming hypothesis is the epigenetic view, which holds that offspring anxiety characteristics develop due to modified gene expression in the genetic parents, in response to environmental influences and stressors (Bartlett et al., 2017; Franklin et al., 2010). The epigenetic view is considered controversial for many reasons, e.g., overreliance on animal models; problems inferring causality due to epigenetic modifications being reversable, and limited ability to disentangle epigenetic changes from genetic and environmental effects (see, e.g., Horsthemke, 2018). It is worth highlighting that anxiety disorders are moderately heritable, and there is evidence that gene-environment interactions and associations partly explain intergenerational transmission (Ask et al., 2021; Craske et al., 2017). However, it has been acknowledged that direct environmental transmission, added to multiple common genetic variants with modest effect sizes, is most likely to explain intergenerational transmission of anxiety (Creswell & Waite, 2015; Purves et al., 2020).

[9]I.e., more infant-directed speech; more positive facial expressions.

There is a rich literature documenting the environmental mechanisms linked to the intergenerational transmission of anxiety (Bögels & Brechman-Toussaint, 2006; Murray et al., 2009; Rapee et al., 2009). Due to the early onset of anxiety disorders in children (5.5. years; Solmi et al., 2022) and the rationale for early identification and prevention of anxiety disorders (the younger children are, the greater their neurodevelopmental plasticity and susceptibility to behaviour modification; Hirshfeld-Becker & Biederman, 2002), here I focus on those identified within early development. Environmental mechanisms that have been associated with increased likelihood of young children developing anxiety disorders include: caregiver modelling of anxiety (Aktar et al., 2013; Aktar & Bögels, 2017; Murray, Pella, et al., 2014; Pass et al., 2012), limited caregiver challenging behaviour[10] (Majdandžić et al., 2014, 2018), and caregiver overcontrol or overprotectiveness (Möller et al., 2016; Van der Bruggen et al., 2008), which may include accommodation of child avoidance behaviours (Lebowitz et al., 2013, 2016, 2019). In preschool aged children, caregiver modelling of anxiety may manifest through a tendency towards more negative and less supportive narratives, i.e., with higher threat attribution and lower encouragement compared to reference parents (Murray, Pella, et al., 2014). In children under 12 months, caregiver modelling of anxiety may include an ‘increase in intensity and frequency of gaze, positive affect, and verbalizations of anxious (*vs.* reference) mothers; so-called exaggerated behavior’ (Aktar & Bögels, 2017, p. 374).

Sometimes collectively referred to as ‘overinvolved’ or ‘intrusive’ caregiving, overcontrolling behaviour refers to caregivers’ excessive help or interference with their child’s behaviour, without taking their needs, interests and desires into account, while overprotective behaviour refers to caregivers being overly cautious towards their child due to concern with their health and safety, e.g. by warning the child for minor dangers, being overly attentive or responsive to signs of child anxiety, or acquiescing to the child’s wish to avoid ambiguous situations (as defined by Möller et al., 2016, p. 20). Observable examples of overinvolved caregiving in early childhood include motor behaviour, such as shielding or blocking children from a low-threat stimulus (infant age 24 months; Buss et al., 2021) and vocal behaviour, such as speaking in ways that demand a response from young children and/or divert their attention (child age 2-4 years; Briscoe et al., 2017; Edison et al., 2011). Heightened physiological reactivity to minor threat has also been observed in anxious caregivers and is thought to index an overprotective response (child age 24 and 12 months; Kalomiris & Kiel, 2016; Smith et al., 2022).

1.3 The role of contingency and synchrony in anxiety transmission

Existing research on how anxiety-related characteristics are transmitted from caregiver to child often use parent-report measures, or aggregate measures of behaviours or traits averaged over a given time

[10] I.e., ‘rough and tumble play’ or encouragement to go outside the child’s comfort zone (Majdandžić et al., 2014).

window; while this has been a generative methodology that has provided us with a substantive evidence base, our understanding of the intergenerational transmission of anxiety may be nuanced by diverse approaches (Perlman et al., 2022). Instead of investigating caregiver traits or behaviours that may be only modestly associated with the development of child anxiety, contemporary models of developmental psychopathology emphasise a dynamic systems perspective, focusing on the ‘underlying dynamic, granular, moment-to-moment interactions between parent and child’ across behavioural and biological levels (Perlman et al., 2022 [p. 111]; Somers et al., 2022; Zhang et al., 2022). Methods focused on fluctuations in caregiver and child bio-behavioural states have the potential to furnish us with a range of theoretical and practical benefits. They may help us to see how daily interactions attune the child to their caregiver’s expression and regulation of anxiety, how these influence infant responses, and how infant responses in turn affect their caregiver’s distress states, in a cascade-like pattern. In turn, this information may provide new risk markers for the development of socio-emotional difficulties and may help identify precise targets for caregiver-infant intervention.

Core to investigations of caregiver-infant dynamics are the concepts of contingency and synchrony. Contingency, sometimes termed ‘sensitivity’, may be defined as ‘behaviour that occurs conditional to the behaviour of the other party’ (Wass et al., 2024., p. 31; see also: Beebe et al., 2016). Attachment theorists also emphasise ‘awareness of infant signals, accurate interpretation [thereof], and prompt response’ in their definitions (Beebe & Steele, 2013, p. 2). Less contingent caregiving is associated with insecure child attachment (Groh et al., 2017), and insecure attachment has, in turn, been associated with the development of child internalising difficulties such as anxiety (though effect sizes are small; d = .15; Groh et al., 2012). Although there are socio-emotional developmental risks associated with less contingent caregiving, there are also risks associated with overly high levels of contingent caregiving behaviour. Numerous studies have demonstrated associations between over-contingency and insecure attachment (Beebe et al., 2011; Beebe et al., 2023; Bornstein & Manian, 2013; McFarland et al., 2020; Mitsven et al., 2022).

High levels of contingency may give rise to high levels of ‘synchrony’ in caregivers and infants, a process by which simultaneous neural, behavioural and physiological processes appear to take place between partners (Butler, 2011; Helm et al., 2018). For example, if partner A smiles and partner B returns the smile, then – so long as the smiles overlap in time – contingency can lead to simultaneously occurring events. While higher levels of caregiver-infant behavioural synchrony have been associated with positive child socio-emotional functioning (e.g., rapport-building; prosocial behaviour; Cirelli et al., 2014; Harrist & Waugh, 2002; Trainor & Cirelli, 2015) and secure child attachment (Feldman, 2017b), initial evidence suggests that overly high levels of caregiver-infant synchrony are not always advantageous. For example, in families with high socio-economic disadvantage, history of maltreatment, or dyads with insecure attachment, more synchrony associates with reduced child self-regulation (DePasquale, 2020; Lunkenheimer et al., 2018; Smith et al., 2016; Suveg et al., 2016).

Mechanisms for how high synchrony confers disadvantage for socio-emotional development are not fully understood (partly as available evidence is largely cross-sectional). Historically, developmentalists have proposed that very high synchrony levels minimise opportunities to practice transitioning between states of mismatch and reparation, a process thought to be necessary for the development of typical regulatory function in the infant (Tronick et al., 1998a). More recently, theorists have suggested that the relationship between high synchrony levels and child socio-emotional difficulties may be explained through 'passive' versus 'active' processes. Passive processes refer to the phenomenon of 'stress contagion'; the automatic parent-child transmission of affective and arousal states, irrespective of direct action or behavioural cues like speech, gaze, or touch (Waters et al., 2014). Another way that passive processes may play a role is through the infant "'piggybacking' on the caregivers' stable physiological rhythms until they show similar physiological rhythms themselves" (Wass et al., 2024, p. 487) – an example of this would be that, if a caregiver's sleep-wake schedule is dysregulated, this can disrupt the infant's ability to develop consistent and stable circadian rhythms (due to, for instance, stimulating engagement during night-time awakenings, or the absence of a dark, quiet house at consistent times); this may risk lower sleep quality, more sleep-wake pattern variability, and atypical socio-emotional functioning (Mäkelä et al., 2021; Sun et al., 2018). By contrast, active processes refer to the adjustments or responses made by the caregiver in reaction to infant cues. For example, minor instances of distress in an infant may provoke heightened reactivity in a stressed caregiver, leading to a response of intense, bursty speech, which may trigger high sustained levels of arousal and associated behavioural signals in the infant, in turn amplifying the caregiver's arousal levels and behavioural response, further triggering the infant (Smith et al., 2023; Smith et al., 2022; Wass et al., 2024). Cumulatively, this may result in a dynamic in which the dyad tends to settle over time, with the possible corollary being chronic activation in the child's stress response system (e.g., hypothalamic-pituitary-adrenal axis), over time recalibrating the child's physiological reactivity such that they are more sensitised to stressors and are slower to calm after exposure to a stressor (Laurent et al., 2016).

Alternatively, high levels of synchrony may confer disadvantages for child socio-emotional functioning through the mechanism of disrupted predictive learning (Hoehl et al., 2021; Nguyen et al., 2024). Consistent cause-and-effect experiences help infants learn how their actions relate to outcomes; when infants express a need through crying, and receive a consistent comforting response, they learn that they can influence their environment and alter their affective states (Köster et al., 2020). Children who experience less consistent or responsive caregiving may adapt their behaviours so as to 'make an effort to become attuned … when interacting with that specific type of parent' (Nguyen et al., 2024, p. 11), with this reflected in higher caregiver-infant synchrony. Inconsistent caregiving (assessed across both moment-to-moment caregiver-infant interaction and longer timescales in the home and family environment) is known to predict reduced effortful control from infancy to adolescence, with poor effortful control representing a risk factor for both internalising and externalising difficulties across the lifespan (Davis & Glynn, 2024). Over the course of development more broadly, unpredictable dyadic relations are thought to increase working memory load and deplete cognitive resources that can be directed towards perception of the other person (Hoehl et al., 2021; Macrae et al., 2008; Miles et al., 2010); in later life when there are high levels of synchrony amid stressful contexts, this is thought to lead to 'empathetic distress rather than concern' wherein one party seeks to escape discomfort rather than support the other (Decety & Meyer, 2008; Hoehl et al., 2021 [p. 13]; Lamm et al., 2016). In addition, very high levels of emotional synchrony are thought to impede the 'self-other' boundaries necessary for perspective-taking and empathy (Galbusera et al., 2019; Hoehl et al., 2021, p. 13). Taking these different mechanistic explanations together, it is possible to see how high levels of caregiver-infant synchrony may scaffold the development of dysregulatory processes.

1.4 Recent advances and the present study

Due to growing evidence showing that caregivers with perinatal anxiety share higher levels of behavioural synchrony with their infants (Beebe et al., 2011; Doba et al., 2022; Granat et al., 2017), caregiver-infant synchrony has been highlighted as a core feature in recent models of the intergenerational transmission of anxiety (Perlman et al., 2022). Recently I have extended our understanding in this area by finding evidence to suggest that anxious parents show higher physiological synchrony with their 12-month-old infants than less anxious parents (Smith et al., 2022). Time series data were collected over the course of the day in the home setting, from a community sample, where parental anxiety was assessed using elevated scores on a generalised screening tool (the GAD-7). The GAD-7 is a screening tool for clinical anxiety that is routinely used in UK clinical services, particularly in primary care, and captures a range of severity including sub-syndromal symptoms. Data were gathered at the physiological level for both adult and child participants given the relevance of this to parent-child anxiety transmission, i.e., because physiological arousal dysregulation is a core feature across anxiety disorders (identified as a maintaining factor of adult generalised anxiety disorder, social anxiety disorder, and panic disorder; Bögels & Lamers, 2002; Brown & McNiff, 2009; Thayer et al., 1996), because physiological hyperarousal in infancy represents a dispositional factor for childhood anxiety (de Vente et al., 2020; Moller et al., 2016), and because fluctuating arousal may serve as a pragmatic index of stress dysregulation in infants who are unable to express their affective states verbally. By examining both child and adult physiological responses, it was also possible to gather continuous information about participants' affective states that may be outside of awareness and thus not readily observable (Blascovich & Mendes, 2010). Data were gathered naturalistically, using innovative wearable technologies, to allow for the capture of real-world interactions between the child and the social environment (including chains of events that are inherently more challenging to capture within the lab-controlled stimulus-response paradigms that characterise much developmental research; see Smith, 2022, pp. 49-50).

In the present study, I aimed to replicate the protocol of the previous study and expand it to introduce novelty. Specifically, the design was altered to investigate whether the patterns seen at 12-months are also manifested earlier in infancy. This is an important question because earlier in infancy the child drives caregiver-infant interaction much less than later on (Green et al., 1980; Lamb, 1977), and therefore depends on their caregivers' observation and interpretation for appropriate contingent responses. For anxious caregivers who vigilantly monitor for signs of infant need (Beebe et al., 2011), this may lead to overly high contingency and synchrony levels. In addition, much of the literature on perinatal depression and caregiver-infant interaction is focused earlier in infancy (<6 months, see, e.g., Field et al., 2009; Murray, 2009; Tsivos et al., 2015); focusing the present study on this earlier age range therefore contributes to aligning the perinatal anxiety and depression evidence bases. Anxiety and depression commonly co-occur, with overlapping maintenance processes (e.g., avoidance, negative cognitive bias; Dennis et al., 2022; Falah-Hassani et al., 2017); by enhancing our understanding of both conditions from early infancy, interventions can be designed to account for both, potentially improving outcomes for both parents and infant. Of note, one further difference from the previous study was to redesign the equipment so that it was possible to measure caregiver-infant proximity, a variable that was not previously controllable, and which possibly exerted a confounding influence over previous analyses investigating the associations between caregiver behaviour and caregiver-infant synchrony; altering the equipment allowed for subsequent analyses to account for this. An examination of how caregiver-infant synchrony varied by proximity as well as caregiver anxiety was of interest given evidence that caregiver-infant bonding and child socio-emotional development are thought to be partly fostered through close contact (e.g., caregiver-newborn skin-to-skin contact is positively related to infant self-regulation and caregiver-infant attachment; Barnett et al., 2022; Feldman, 2004). On an exploratory level, I was also interested in how proximity might relate to synchrony in caregivers with higher anxiety levels, given the possibility of caregivers indirectly seeking greater proximity with their infants as a function of overprotective parenting behaviour (e.g., holding infants closer in public, delaying or avoiding separation, responding quickly to minor distress by picking the infant up and holding them more frequently or for extended periods).

I also aimed to introduce novelty in the present study by examining infant and caregiver reactivity to caregiving behaviours associated with anxiety. Caregiver behaviour such as speech and touch have been identified in previous studies as amplifying 'stress contagion' in caregiver-infant dyads, and acoustic speech parameters (e.g., vocal intensity, burstiness) have previously been found to associate with increased caregiver-infant stress contagion within the context of parental anxiety (Smith et al., 2023; Waters et al., 2017). To contribute new knowledge in this area, I examined the semantic content of speech and the impact of this on infant and caregiver arousal reactivity. 'Semantic content' includes words and phrases, such as commands/directives, that signify intrusion or control, behaviours noted in parents with elevated anxiety (Briscoe et al., 2017; Edison et al., 2011; Taylor et al., 2009). Such an investigation inheres the assumption that the child has a basic understanding of caregiver speech. Consequently, it was important to consider the age at which infants could perceive and comprehend their caregivers' vocalisations. Around 6-9 months, infants become able to differentiate simple imperatives or commands; they can distinguish whether their social partner's actions are purposeful or non-purposeful (Behne et al., 2005) and can link their caregiver's words to referents over a range of categories (e.g., food, body-part terms; Bergelson & Swingley, 2012). Thus, where available, with reduced power, exploratory associations were investigated in a subset of the sample seen at 10-months, examining how intrusive caregiver speech associates with infant and caregiver reactivity and caregiver anxiety levels.

Overall, to address the main research question of how anxious caregiving manifests early in infancy, I used miniaturised ECG and audio-recording devices worn by caregivers and infants at home during the day, specifically examining how caregiver-infant synchrony varies by caregiver anxiety level.[11] This allowed me to test my primary hypothesis that, given initial evidence for elevated synchrony among anxious caregivers and 1-year-old infants (approximately; Doba et al., 2022; Granat et al., 2017; Smith et al., 2022), caregiver-infant physiological synchrony will also be higher in dyads with more anxious caregivers earlier in infancy, by the end of the first half of the first year (circa 5 months). My secondary hypothesis was that caregiver-infant synchrony is influenced by caregiver-infant proximity, such that (a) caregiver-infant synchrony is higher for caregivers and infants who are closer to one another, and (b) the strength of this relationship is greater in more anxious caregivers and their infants compared to less anxious caregivers and infants. Finally, for a subset of the sample seen at 10 months, I also conducted exploratory analyses examining infant and caregiver reactivity levels around vocal indices of intrusive caregiving behaviour. For this, I hypothesised that infant and caregiver reactivity levels would change around specific caregiver vocalisations (commands/directives, choice questions, and 'what/where/how/why' questions), with greater change in physiological arousal observable in dyads where the caregiver has higher anxiety scores. Taken together, my aim was to elucidate how perinatal anxiety impacts moment-to-moment dyadic relations in early infancy, with a view to informing early intervention.

[11] The equipment and protocol were co-developed by myself and colleague SW, with initial piloting carried out by me. Principal data collection was provided by the BabyDev Lab at the University of East London. I led on development of the research questions and proposal, as well as analysis and interpretation of the psychobiological and behavioural data.

2. Method

2.1 Participants

Participants were recruited between September 2021 and July 2023, within the region of north-east London in the United Kingdom. Typically developing infants and their caregivers were recruited via local nurseries, preschools, infant groups, community centres, social media campaigns, and word-of-mouth (with participating caregivers asked if their respective networks would like further information regarding participation). Marketing materials for recruitment are presented in Appendix section 3. Ethical approval for the study was given by the research ethics committee at the University of East London (reference: ETH2021-0076). In total, 94 caregiver-infant dyads were recruited, of which, at 5 months, usable paired autonomic data were available from 89 dyads and complete caregiver anxiety data were available from 77. Due to missing autonomic data[12], 20 dyads were excluded, leaving 57 dyads with fully usable data at 5 months (see Table 1). Of these, 31 had complete caregiver anxiety and usable audio data available at 10 months. Demographic characteristics of the main sample are presented in Table 1. It is important to note that the sample did not include families where the primary day-time caregiver was a man or non-binary person, due to the inadequate number of such participants for a properly gender-matched sample. Consequently, all the caregivers involved in the study identified as women. Additionally, specific enquiries about the genetic relationship between the participants and their infants were not made. All participants self-identified as mothers. Exclusion criteria included cardiovascular, neurological, or rare genetic conditions; unadjusted visual difficulties, and differences related to developmental stage (e.g., infants with known developmental delay or premature birth; caregivers under the age of 18 years old). Infants were included if they were aged no more than 5 months (+ 4 weeks) at the point of the first home visit. Data were analysed cross-sectionally. The minimum sample size required for analyses was calculated using existing comparable data on the primary outcome: level of caregiver-infant physiological synchrony. The sample size for the present study was determined through a power analysis using G*power, which indicated that, for an independent t-test with one-tailed significance of .05, 76 participants are needed to detect d = .58 with 80% power. Post hoc computations indicate that a sample of 57 dyads could detect an effect size of d = .60 with 70% power (and d = .70 with 80% power). The data for the power analysis came from a previous study using a similar protocol, where infants were aged 12 months: previous analyses examined differences of infants grouped by higher/lower parental anxiety, based on a median split of the GAD-7 screening tool (Smith et al., 2022). Using co-occurring physiological arousal peaks as the primary outcome measure, Cohen's d was calculated to be .58.

[12]Further detail on assumptions for missing data is presented in Appendix section 2.

2.2 Procedure

The procedure followed processes documented in previous papers (Smith et al., 2023; Wass et al., 2019). Participants were asked to select a typical day, one where they would be with their infant for the entire day. A researcher visited the home early in the morning to install the wearable equipment and returned in the late afternoon to collect it. The equipment recorded an average of 6.63 hours at the five-month visit (*SD* = 1.85). The equipment included two wearable devices, one each for infant and caregiver, containing an electrocardiogram (ECG; recording at 250Hz), microphone (48kHz), proximity sensor (1Hz), accelerometer (40Hz) and GPS (1Hz), with data stored on an internal miniaturised flash memory card. The infant's device was embedded within an internal chest pocket of a bodysuit, with apertures allowing ECG and microphone leads to pass through. This, in turn, allowed for the microphone to be clipped to the top-right side of the vest, and ECG electrodes to be attached to the infant's torso using Ag-CI electrodes in a modified lead II position. The caregiver's device was contained within the pocket of an elastic chest belt. ECG electrodes were attached similarly to the infants, while the microphone was attached onto caregivers' own clothes. See Figure 1 below for imagery of the equipment. Of note, recent research on caregiver attitudes to wearable technology used for in-home infant monitoring (encompassing considerations of the viability, acceptability, comfort, privacy, data access and safety of these technologies) has indicated generally positive attitudes, particularly for infant-friendly wearable devices such as the sensing body suits described above (see e.g., Fish & Jones, 2021, with results unchanged across caregivers of lower and higher socio-economic status; Prioreschi et al., 2018).

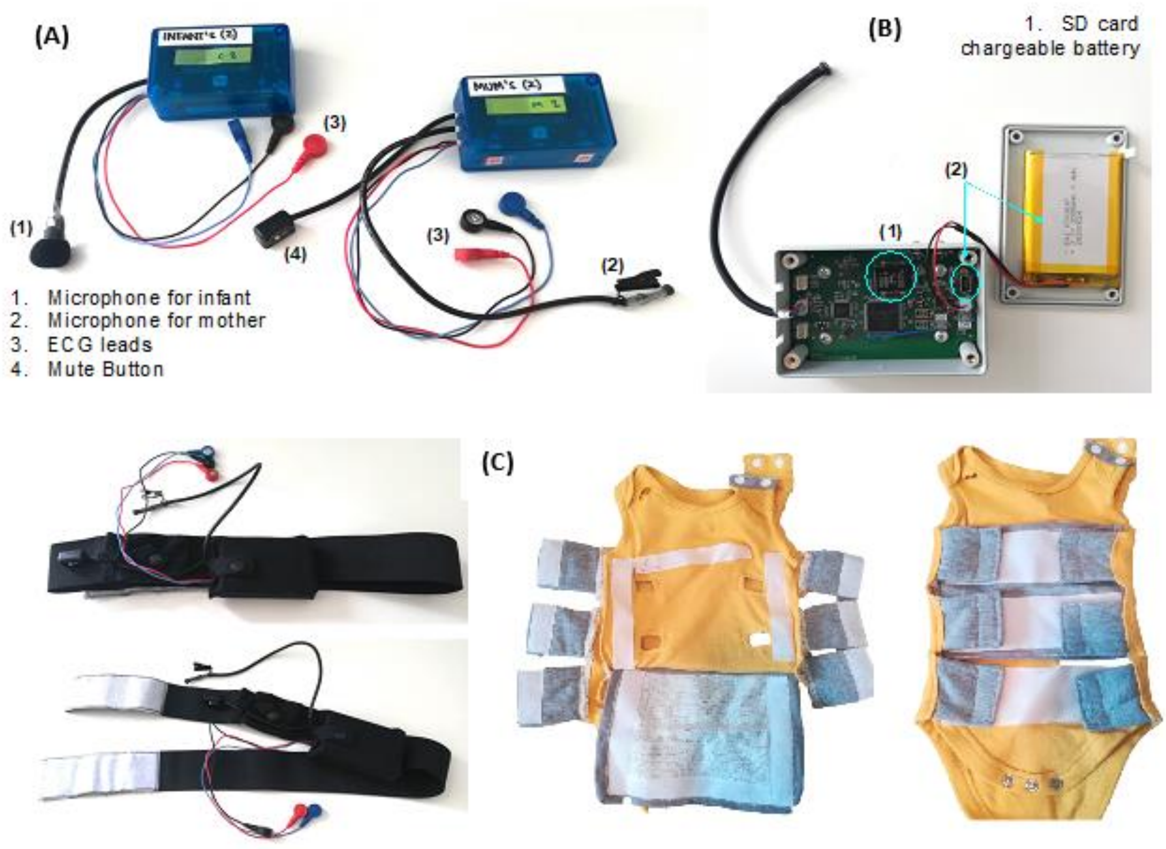

Figure 1. Home wearable equipment, including (A) devices for both infant and caregiver, with microphone leads, ECG leads and a mute button shown for privacy; (B) printed circuit board, contained within device hardware, showing SD card and rechargeable battery; (C) garments in which hardware was embedded; adult elastic chest belt and internal chest pocket of baby bodysuit.

2.3. Quantification and statistical analysis

2.3.1 Raw data structure

The proximity sensor collected data regarding the distance between the paired devices in centimetres, while the ECG collected data including the value of the trace, the time in seconds of each reading, and confidence intervals for data quality. The infant and caregiver's devices were synchronised at the beginning of the day; the caregiver device's GPS signal allowed for finding and pairing with the infant device, while also searching and obtaining the correct date and time with reference to Coordinated Universal Time. ECG data were originally recorded at 250Hz, proximity data sampled at 1Hz, actigraphy data sampled at 40Hz, and audio data recorded at 48kHz.

2.3.2 Preprocessing of autonomic measure

To establish the autonomic measure for the present study, the ECG data required preprocessing. First, beats per minute (BPM) were processed by down-sampling to 1Hz (one sample per second) and z-scored the data. Heart rate variability (HRV) was calculated with the root mean square of successive differences (RMSSD), using the RMSSD function from HRVTool (Vollmer, 2015, 2019) before z-scoring the data. RMSSD is the standard statistical measure of HRV and involves measuring the difference in time between each heartbeat.[13] In addition, the actigraphy data were processed. This involved the application of a low-pass filter with a cut-off of 0.1Hz to remove high-frequency noise, calculating the derivative and average of all three axes of accelerometer recordings, and down-sampling the data to 1Hz by calculating the mean from all readings comprised in each second and normalising it (Wass et al., 2019). Data were then z-scored. An arousal composite was subsequently calculated by averaging the inverted z-scored HRV data with z-scored actigraphy and BPM data. Outliers in the BPM data were defined by values 2.5 inter-quartile ranges above the upper quartile and below the lower quartile; outliers were interpolated using the MATLAB function ‘fillmissing’, as demonstrated in recent reports (Amadó et al., 2023).

2.3.3 Preprocessing of proximity and questionnaire data

For all analyses, and for each dyad, the infant file was used to obtain the proximity data. If this was missing, the caregiver file was used. Where proximity was not detected, discrete missing values were assigned.

For Analysis 3 (see section 2.3.8), the composite arousal score for the 10-month timepoint was calculated from both caregiver and infant data, after which the two groups were created. The groups were split as per Analysis 1 (see section 2.3.6) by clinical thresholds (see section 2.3.5) using the GAD-7 data collected at the 10-month timepoint. If the 10-month GAD-7 data did not exist, the 5-month data were used instead (on the basis that GAD-7 scores show stability over time and predictive value; Byrd-Bredbenner et al., 2020; Stochl et al., 2022). Subsequently the vocalisation onsets were identified and located in the ECG data; events of interest were identified by selecting five minutes before and after each vocalisation.

2.3.4 Vocal coding

To measure caregiver vocalisations of interest, an open-source speech processing model was used to classify audio segments into adult female speech, adult male speech, key-child (i.e., the infant wearing the device) vocalisations, and other child vocalisations. Vocalisation onset and offset times were also identified via the model. Details regarding the model structure and how it is trained are presented in recent reports (Gautheron et al., 2020). Of note, the model is based on over 250 hours of recordings of families from multilingual contexts (including multiple languages with diverse typological

[13]Heart rate variability refers to the variation in time between consecutive heartbeats. It is one of several measures reflecting activity in the autonomic nervous system (the fast-acting neural substrate of the physiological stress response; Cacioppo et al., 2007), and, as such, is conceptualised within this study as one index of physiological stress. Here, HRV is combined with other indices of physiological arousal (BPM, actigraphy) to create a composite measure of physiological arousal. Detail on the justification for use of composite autonomic arousal measure are given in previous related reports (Smith, 2022, p. 181).

characteristics). For the present study, specific hours from the day long recording were selected for manual coding according to several criteria: amount of time spent at home, amount of time infant spent awake, and amount of usable ECG data available for both caregiver and infant. An algorithm identified which hours to code based on which scored highest across these criteria. Subsequently, two undergraduate psychology students manually coded who was speaking, the context (i.e., who the caregiver was speaking to) and the type of vocalisation according to predefined categories representing 'controlling' vocal behaviour (i.e., commands/directives; choice questions; process questions) among a list of 38 vocal categories. Example statements include 'look at this', 'hold this', 'stop crying', 'move your hands' (commands/directives); 'do you want this?', 'shall we stop this?' (choice questions), and 'what is this?', 'why is this here?' (process [what, why, where, when, how] questions). Coders were masked to the planned analyses and group status of each participant. Due to labour intensive coding demands, only one to two hours of data were coded per dyad. The coders received initial training from a post-doctoral researcher using the original data and ongoing feedback for the first six hours of coding. To assess inter-rater reliability, 10% of the sample was double-coded; Cohen's *k* was .63 (commands/directives), .68 (process questions) and .59 (choice questions), values considered acceptable (McHugh, 2012).

2.3.5 Caregiver anxiety measure

The Generalized Anxiety Disorder 7-item (GAD-7) questionnaire was used to screen caregivers for anxiety. The GAD-7 surveys symptoms of generalised anxiety over the preceding fortnight, asking respondents to rate how often they have experienced various thoughts and behaviours on a 4-point scale, ranging from 0 (not at all) to 3 (nearly every day). Where possible, the GAD-7 score was analysed as a continuous variable. When required for time series analysis, the sample was split by GAD-7 score into two groups based on clinical thresholding; the 'low' group included those meeting no threshold for anxiety (total score <4), and the 'moderate' group included those with mild (≥ 5), moderate (≥ 10) or severe anxiety (≥ 15; Spitzer et al., 2006). Justifications for use of the GAD-7 tool are given in previous reports (Smith et al., 2023; Smith et al., 2022), i.e., while acknowledging individual differences among specific anxiety disorders, the GAD-7 acts as a global 'catch-all' measure of anxiety that has been validated in studies of both clinical and nonclinical populations, with scores above 6 indicative of mild to moderate anxiety (Löwe et al., 2008; Norton & Paulus, 2016). Cronbach's alpha for internal consistency was .79 at 5 months and .88 at 10 months. Recent research on prenatal anxiety has highlighted that anxiety scales developed for use in the general population may, as they are applied to perinatal contexts, be limited due to emphasis on physical symptoms that are also commonly experienced in pregnancy (e.g., DASS, STAI, GAD-2; Sinesi et al., 2022). This is less applicable to the present study of postnatal anxiety, as the GAD-7 screening tool asks respondents to rate, over the last two weeks, 'how often you have been bothered by the following problems' for the following items: (1) Feeling nervous, anxious, or on edge; (2) Not being able to stop or control worrying; (3) Worrying too much about different things; (4) Trouble relaxing; (5) Being so restless that it is hard to sit still; (6) Becoming easily annoyed or irritable, and (7) Feeling afraid, as if something awful might happen (Spitzer et al., 2006).

2.3.6 Analysis 1: cross-correlation analyses to examine caregiver-infant synchrony in low *vs.* moderate anxiety groups at 5 months

For Analysis 1, based on the main sample at the 5-months timepoint, a cross-correlation function was calculated using the programming language MATLAB. A cross correlation allows for the examination of both caregiver and infant ECG data as time series, looking at whether the series appear to match one another, or where one appears to control or influence the other; in effect, a cross-correlation can answer the question: ‘when partner A is high in physiological arousal, is partner B also high in physiological arousal?’ Technically, cross-correlations measure how similar two time series are as a function of displacing one relative to the other. This is computed by incrementally shifting one time series back by a ‘lag’ and repeatedly calculating correlations between the two signals. For the present study, all the datasets (i.e., infant ECG, caregiver ECG, proximity data) were first cropped to the same length, after which all the data captured during infant sleep or when caregiver and infant were >2m apart were excluded. The cross-correlation function was computed for the two groups separately (low and moderate anxiety). To compare whether, overall, there was a statistically significant difference between low and moderate anxiety groups, a permutation-based clustering (CBP) test was used. Further sensitivity analyses using different time lags were conducted, as were analyses where the groups were split differently.

2.3.7 Analysis 2: sliding window correlation analyses to examine caregiver-infant synchrony in low *vs.* moderate anxiety groups at 5 months

An alternative technique for examining the association between infant and caregiver physiological states throughout a day was also used. Using data from the whole day at the 5-month timepoint, a Sliding Window Correlation (SWC) was calculated, allowing me to look at the strength of the association between caregiver and infant physiological signals over a specific, continuously shifting time period. This analysis was conducted for the two groups (low *vs.* moderate anxiety). This involved four key steps. Firstly, dyads with less than one hour of autonomic data were filtered out, by calculating the hours between the start and end time. The filter then examined any recording of >1 hour data and ensured discrete values were present (*vs.* missing data). Secondly, all the readings from when the infant were asleep were excluded. Thirdly, the first and last second of available data were identified in both infant and caregiver datasets; the sliding window correlation was then started on the first second whereby an ECG signal was acquired for both caregiver and infant. A correlation was not calculated if the window had >40% missing data. To compare whether, overall, differences in the SWC between low *vs.* moderate anxiety groups were statistically significant, permutation-based clustering analyses were used; note that such analyses help to differentiate ‘real’ trends from random fluctuations in data with a time dimension. Further sensitivity analyses using different lengths for the sliding window were conducted, as were analyses where the groups were split differently. A correlation was also conducted between SWC results and proximity.

2.3.8 Analysis 3: caregiver and infant physiological sequelae following anxious caregiver ‘intrusive’ vocalisations at 10 months

For Analysis 3, based on a subset of the main sample (*N* = 31) at the 10-month timepoint, calculations were performed regarding infant and caregiver arousal changes around caregiver vocal events. Due to the small sample size available, these analyses were conducted exploratorily. A linear mixed effects model was computed to examine the relationship between arousal change around vocal events and GAD-7 scores, controlling for individual differences in participants’ reactivity levels. This allowed for examination of how changes in caregiver GAD-7 score are associated with caregiver or infant arousal change (i.e., how arousal change varies as a function of caregiver anxiety). Based on previous research identifying caregiver and infant arousal change around child vocalisations (Perapoch Amado et al., 2023), change in arousal was calculated by taking the average arousal from 30 seconds immediately after the vocalisation and subtracting the average arousal from a baseline (i.e., one minute immediately before the vocalisation). A linear mixed-effects model was fitted to the data using the ‘fitlme’ function call in MATLAB. Caregiver or infant arousal change around a vocal event was the response variable, with GAD-7 score the fixed-effect predictor, and random intercepts included for each individual participant. Random effects were accounted for by considering random intercepts per participant; each individual participant could have their own varying baseline level of arousal reactivity, but the effect of caregiver anxiety was assumed to be fixed across all participants. This model is recommended in studies with repeated observations such as time series data (Oberg & Mahoney, 2007).

3. Results

3.1 Descriptive analyses

At the five-months timepoint, the mean time in minutes that the wearables were recording was 400.2 (*SD* = 118.8) for the low anxiety group, and 393 (*SD* = 99.6) for the moderate anxiety group. There were no significant differences in recording time between groups (t(62) = 0.28, *p* = .79). At 5 months, the low anxiety group scores ranged between 0 and 4 (*M* = 2.47, *SD* = 1.45) and the moderate anxiety group scores ranged between 5 and 16 (*M* = 7.59, *SD* = 2.69). At 10 months, the low anxiety group scores ranged between 0 and 4 (*M* = 2.39, *SD* = 1.37) and the moderate anxiety group scores ranged between 5 and 20 (*M* = 8.6, *SD* = 4.99). For the whole sample, the mean GAD-7 scores at 5 and 10 months were 4.24 (*SD* = 3.13, range = 0-16) and 4.03 (*SD* = 3.88, range = 0-20) respectively. Demographic characteristics of the main sample are presented in Table 1 (with further detail regarding the subgroups used in sensitivity analyses presented in Table S1). Due to the small frequencies in the contingency table, Fisher's Exact Test was conducted to assess the association between the two groups (low *vs.* moderate anxiety) across three categories of household income (>£80K, £51-80K and £36-51K) and four categories of maternal education (post-graduate degree, degree, A Levels, GCSEs) at 5 months and 10 months. Analyses indicated no statistically significant associations between the variables at 5 months (all *ps* = .28) and 10 months (*p* = .52 for income and *p* = .41 for education). Group comparisons for infant ethnicity were incalculable due to sparse data across seven categories.

For Analysis 3, a total of 4020 minutes of audio data were coded across 35 participants. All participants had 120 minutes of data coded, except three participants for whom only 60 minutes were coded. Of these 35 participants, two were missing GAD-7 data and two did not feature vocalisations of interest, leaving 31 total participants. Of these, 21 were classed as 'low anxiety' and 10 as 'moderate anxiety.' Across all participants, the mean number of vocalisations per 60 minutes were: (A) commands/directives, *M* = 12.7, *SD* = 14.7; (B) choice or 'yes/no' questions, *M* = 19.7, *SD* = 21.5, and (C) process questions (e.g., wh-type questions and how questions), *M* = 8.63, *SD* = 13.1. Speech categories were informed by comparable studies (Briscoe et al., 2017; Edison et al., 2011; Taylor et al., 2009).

		Five-months (*N* = 57)		Ten-months (*N* = 31)	
		Low anxiety (N = 36)	Moderate anxiety (N = 21)	Low anxiety (N = 21)	Moderate anxiety (N = 10)
	Infant age (mos) – mean (*SD*)	5.15 (.67)	5.36 (.75)	10.25 (.45)	10.20 (.45)
	Gender (N (%) female)	16 (44)	10 (48)	8 (38)	6 (60)
Infant ethnicity N (%)	White British	15 (42)	7 (33)	11 (52)	2 (20)
	White Other	1 (3)	2 (10)	0 (0)	1 (10)
	Afro-Caribbean	1 (3)	0 (0)	1 (5)	0 (0)
	South-east Asian	2 (6)	0 (0)	1 (5)	0 (0)
	Mixed – White/Afro-Caribbean	1 (3)	0 (0)	0 (0)	0 (0)
	Mixed – White/Asian	4 (11)	3 (14)	2 (10)	1 (10)
	Other Mixed	3 (8)	2 (10)	2 (10)	2 (20)
Maternal education (%)	Postgraduate	14 (39)	4 (19)	6 (29)	3 (30)
	Undergraduate	12 (33)	9 (43)	8 (38)	2 (20)
	A Level	3 (8)	0 (0)	2 (10)	0 (0)
	GCSE	1 (3)	1 (5)	0 (0)	1 (10)
	No formal qualification	0 (0)	0	0 (0)	0 (0)
Household income (%)	>£80k	17 (47)	6 (29)	10 (48)	3 (30)
	£51-£80k	6 (17)	6 (29)	3 (14)	3 (30)
	£36-51k	1 (3)	0 (0)	1 (5)	0 (0)
	<£36	0 (0)	0 (0)	0 (0)	0 (0)

Table 1. Demographic characteristics of sample at 5-months and 10-months, split by low/moderate GAD-7 scores.

3.2 Analysis 1: cross-correlation analyses to examine caregiver-infant synchrony in low *vs.* moderate anxiety groups at 5 months

This analysis investigated the association between infant and caregiver physiological states throughout a day. All the moments where proximity was <2 metres and infants were awake were taken and a cross-correlation was run between infant and caregiver arousal. The main results from the cross-correlation analyses are presented below using a maximum lag of 10 minutes. Results show no difference in sequential synchrony between low and moderate anxiety groups in the main analysis (see Fig 2: all *ps* > .025, including t = 0, r_{IAPA} = 1.2 *vs.* 1.5, *p* > .025).[14]

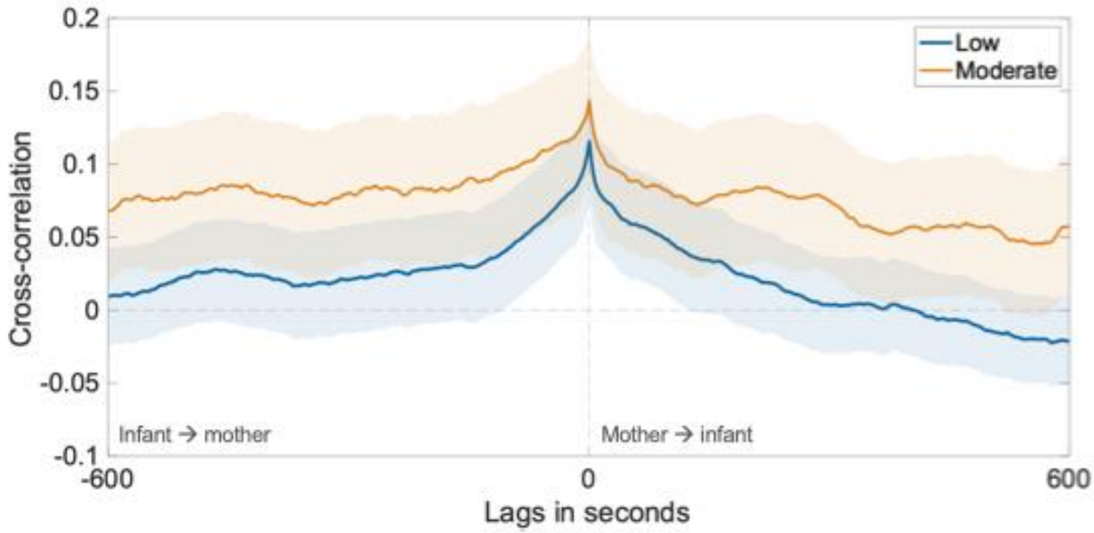

Figure 2. Results from the cross-correlation analysis at 5 months. The low anxiety group is represented by the blue line (*N* = 34) and the moderate anxiety group is represented by the orange line (*N* = 21).[15] Time = 0 on the *x* axis represents a positive cross-correlation (when caregiver is high in arousal, infant is high). Points marked beneath 0 denote negative cross-correlation (e.g., caregiver is low, infant is high).

To explore the consistency of associations, follow-up ('sensitivity') analyses were also performed based on splitting groups based on the top *vs.* bottom 20^{th} percentile of GAD-7 scores, as well as pre-defined extreme values within the dataset (total score <2 *vs.* >10; see Figure 3 below). These analyses indicated a pattern whereby the group with moderate anxiety show higher values than the lower anxiety group; this pattern is present and amplified in all sensitivity analyses. Though the conditions of CBP testing

[14]Where IAPA denotes infant arousal x parent arousal. Note that the CBP test works by identifying significant data clusters and does not yield discrete p-values (e.g., p-value, t-value) without significant findings. If no significant clusters are detected, the outcome is explicitly stated as 'no significant clusters found.' The CBP test is designed to iteratively search for significant clusters above a certain threshold (e.g., *p* = .025), reducing type I errors associated with multiple comparisons. The alpha level was set in line with two-tailed hypothesis testing to provide robustness against random variation in the data.
[15]Group sample sizes differ slightly from those previously outlined due to filtering by proximity <2M and then only including these datasets with more than one hour of data.

prevented an analysis of statistically significant difference, visual inspection indicates the trend is stronger in these analyses. Of note, these follow-up analyses were conducted exploratorily due to a primary focus on replicating the same analyses conducted in a previous study (hence adherence to one analytic method; Smith et al., 2022).

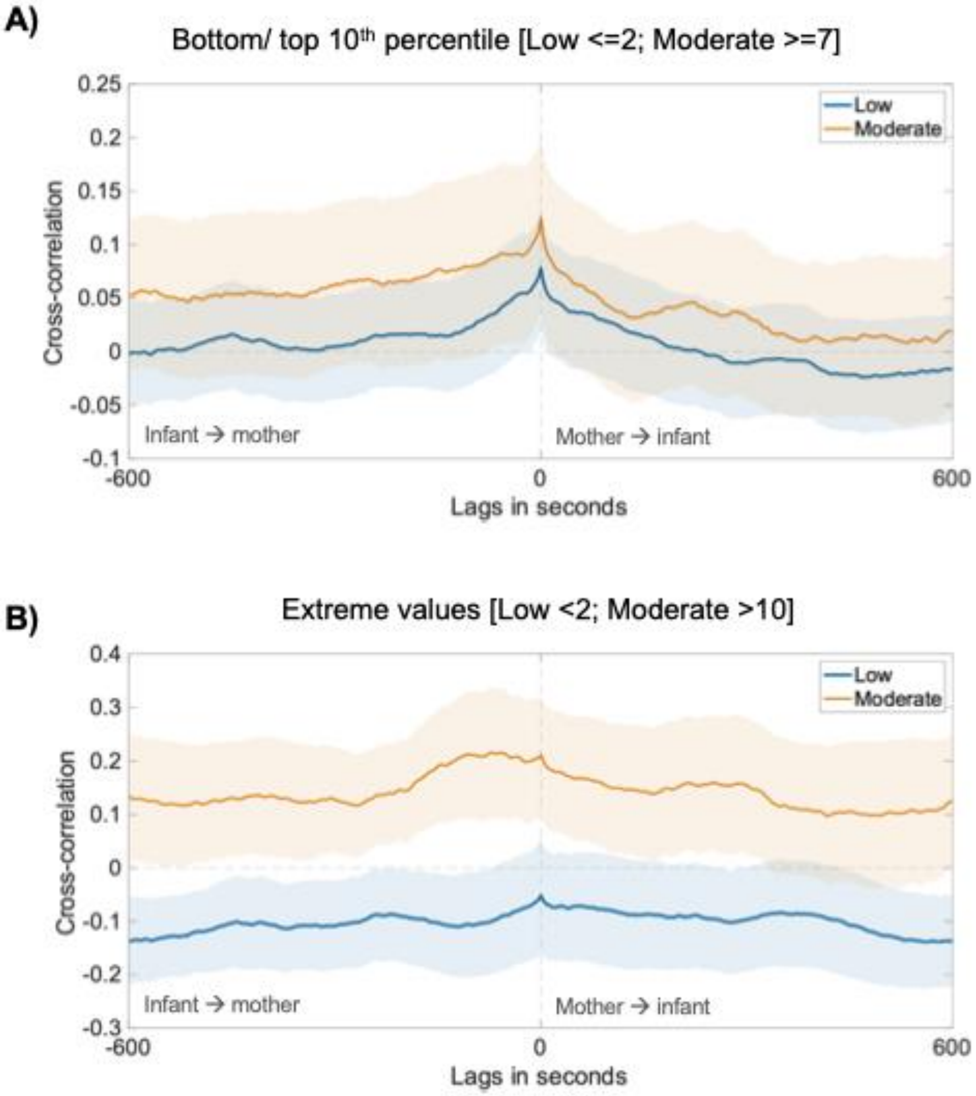

Figure 3. Same cross-correlation analysis at 5 months using a maximum lag of 10 minutes but splitting the groups differently: (A) groups are split based on top and bottom 20th percentile; blue line represents low anxiety group (*N* = 16) and the orange line represents the moderate anxiety group (*N* = 12); (B) based on predefined extreme values (low anxiety, *N* = 6; moderate anxiety, *N* = 4).

3.3 Analysis 2: sliding window correlation analyses to examine caregiver-infant synchrony in low *vs*. moderate anxiety groups at 5 months

For the sliding window correlation analysis, results showed no differences in concurrent synchrony between low and moderate anxiety groups ($p > .025$, Fig 4A). Very similar results were found using different thresholds. A significant negative correlation was found between SWC results and proximity for both low (rho = -.21, $p < .001$) and moderate (rho = -.24, $p < .001$) groups. Results showed that synchrony increases as proximity between dyad decreases (i.e., members of the dyad are closer to each other). The same pattern of results can be seen in all sensitivity analysis (see Figure S1 and S2 in Appendix). A z-test revealed no statistically significant group differences in the relationship between synchrony and proximity ($z = .11$, $p = .46$).

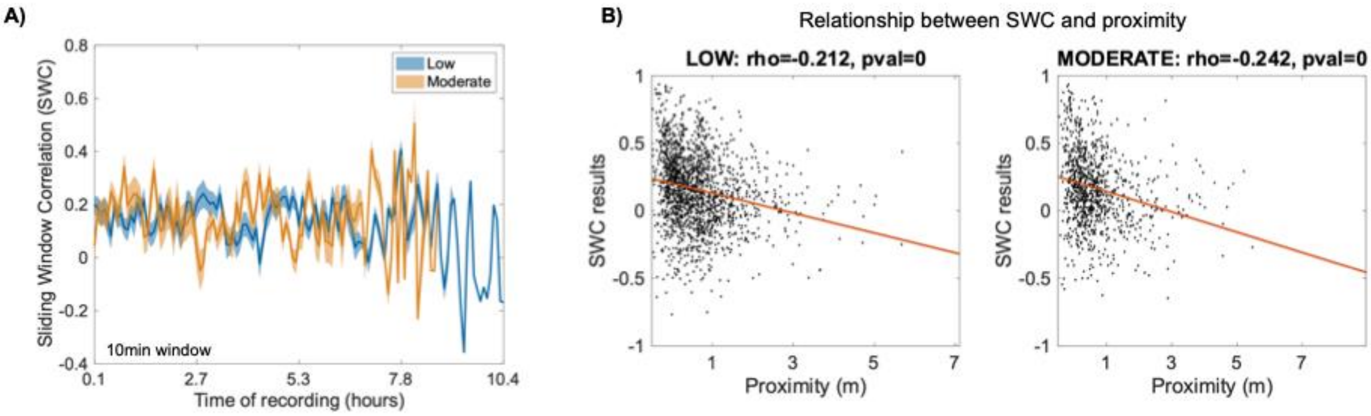

Figure 4. Results from sliding window correlation using a sliding window of 10 minutes. (A) Shows SWC in low anxiety group (blue, $N = 36$) and moderate anxiety group (orange, $N = 21$) with no statistically significant differences ($p > .025$). (B) shows relationship between proximity and concurrent synchrony between infant and caregiver physiological states, showing that synchrony correlates negatively with proximity.

3.4 Analysis 3: caregiver and infant physiological sequelae following anxious caregiver ‘intrusive’ vocalisations at 10 months

Analysis 3 investigated how caregivers and infants react physiologically to different types of caregiver vocalisations and how this reaction associates with GAD-7 scores, using a linear mixed-effects model (LME). Before this, preliminary analyses regarding different types of vocalisations were conducted. Visual inspection of histograms indicated that caregiver vocalisation variables were generally positively skewed with a right-skewed distribution (see Figure S3 in Appendix). Means and standard deviations for the variables of interest are presented below in Table 2 and Figure 5; these indicate the average number of times caregivers vocalised in a particular way per hour. To examine group differences between the low ($N = 10$) and moderate anxiety groups ($N = 21$) regarding frequency of different caregiver vocalisations, Mann-Whitney U tests were conducted. Results indicated no statistically significant differences between the groups regarding the distribution of process questions: $U = 63.0$, $p = .35$, with a mean rank of 15 for the low anxiety group and 12 for the moderate anxiety group. Similarly, there were no statistically significant group differences regarding the distribution of choice questions ($U = 80.5$, $p = .90$, with a mean rank of 13.97 for the low anxiety group and 14.06 for the moderate anxiety group) and commands/directives ($U = 53.0$, $p = .15$, with a mean rank of 15.56 for the low anxiety group and 10.89 for the moderate anxiety group).

	M (SD)	
	Low anxiety	Moderate anxiety
Process questions	22.78 (23.54)	15.67 (14.84)
Choice questions	49.56 (46.42)	40.0 (25.89)
Commands/directives	33.61 (32.42)	18.11 (20.52)

Table 2. Means and standard deviations for the different types of caregiver vocalisations at 10 months, split by anxiety group.

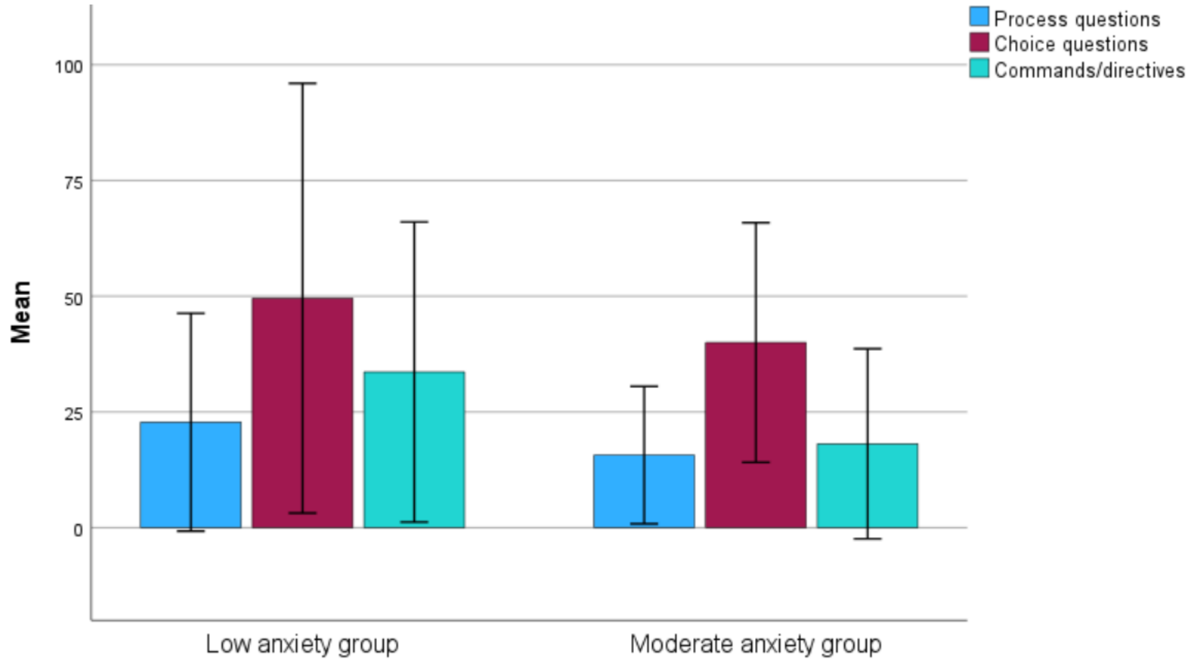

Figure 5. Means for the different types of caregiver vocalisations at 10 months (process questions, choice questions, commands/directives), split by anxiety group. Error bars represent 1 +/- standard deviations.

For the LME, GAD-7 scores were used as a continuum. A different LME was used for each vocalisation of interest and performed for both caregivers and infants separately. The results are presented in Table 3 and Figure 6 below. Small but significant effects were observed for Model 4, indicating that infant arousal change is explained by caregiver GAD-7 score for choice questions, such that there is more infant arousal change around choice questions with higher GAD-7 scores. Similarly small but significant effects were observed for Model 5, which indicated that caregiver arousal change is explained by caregiver GAD-7 score for commands/directives, such that there is more caregiver arousal change around commands/directives with higher GAD-7 scores.

	Predictor * response variable	***b***	**SE**	**df**	***t***	***p***
Model 1	caregiver anxiety level * caregiver arousal change around process questions	-0.0013	0.00392	475	-0.32	0.75
Model 2	caregiver anxiety level * infant arousal change around process questions	-0.0013	0.00392	475	-0.32	0.75
Model 3	caregiver anxiety level * caregiver arousal change around choice questions	-0.0021	0.00327	943	-0.63	0.53
Model 4	caregiver anxiety level * infant arousal change around choice questions	0.0072	0.00365	1112	1.98	0.048
Model 5	caregiver anxiety level * caregiver arousal change around commands/directives	0.0205	0.00450	611	4.55	< .001
Model 6	caregiver anxiety level * infant arousal change around commands/directives	0.0007	0.0066	668	0.1105	0.91

Table 3. Results of Linear Mixed Effects Models at 10 months. Model 1 = caregiver arousal change around process questions vocalisations; Model 2 = Infant arousal change around process questions vocalisations; Model 3 = Caregiver arousal change around choice questions vocalisations; Model 4 = Infant arousal change around choice questions vocalisations; Model 5 = Caregiver arousal change around commands/directive vocalisations; Model 6 = Infant arousal change around commands/directive vocalisations; *b* = regression coefficient; SE = standard error; df = degrees of freedom; *t* = t-value; *p* = p-value.

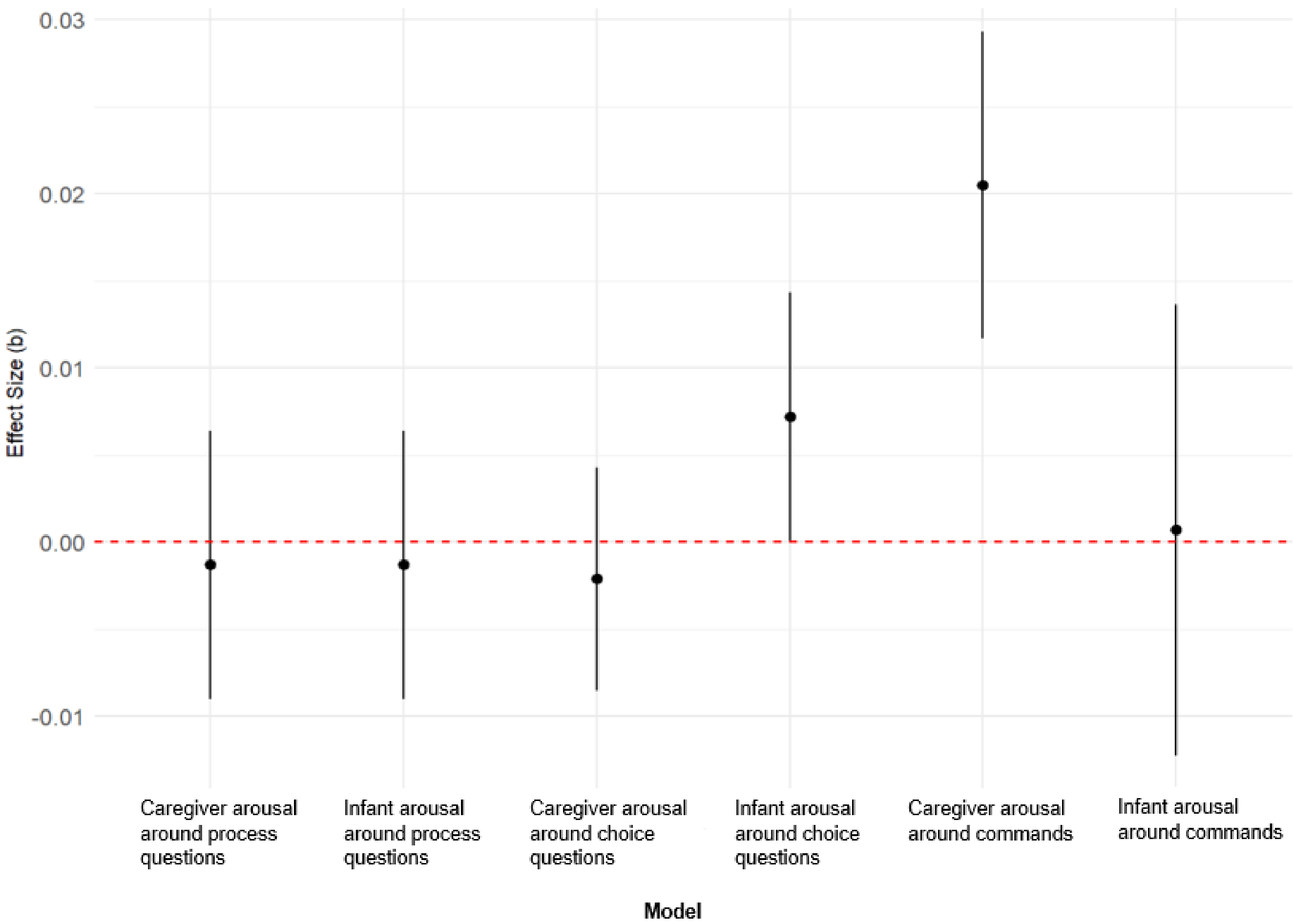

Figure 6. Plot showing the results of the six linear mixed effects models for Analysis 3. Each point represents the estimated effect size (*b*) for the model, and the red dashed line represents a zero-effect. Vertical lines extending from each point represent a 95% confidence interval; if the entire vertical line falls on one side of the zero-effect line, the effect is considered statistically significant. The position of the point on the *y* axis indicates the magnitude and direction of effect. Points above the horizontal zero-effect line indicate a positive effect and points below indicate a negative effect.

4. Discussion

In the present study, I aimed to examine how caregiver-infant interaction dynamics are impacted by perinatal anxiety. Primarily I sought to investigate the relationship between caregiver-infant physiological synchrony and perinatal anxiety when infants were five months old. Exploratory analyses were also conducted to examine how infant and caregiver arousal at 10-months fluctuated around intrusive caregiver behaviour, indexed by vocalisations associated with conversational control (e.g., commands/directives, choice questions, process questions). These analyses were based on novel methods with the potential to generate rich theoretical insights (Dale et al., 2023); data were collected in the community from wearable ECG and audio-recording devices that participants wore for day-long periods in their own environments, without researchers present.

Though confirmatory analyses did not generate statistically significant results, sensitivity analyses showed that there was a consistent pattern showing higher synchrony between moderately anxious caregivers and five-month-old infants compared to dyads where the caregiver did not have anxiety. Though results do not replicate moderate to strong associations observed elsewhere (Doba et al., 2022; Granat et al., 2017; Smith et al., 2022), this trend is consistent with research showing that higher caregiver anxiety in the perinatal period associates with higher caregiver-infant synchrony. This pattern of results, while in need of cautious interpretation due to power and sampling limitations, may contribute to the midrange model of contingent caregiving, which posits that high, sustained levels of caregiver-infant synchrony may be atypical, and that a midrange of synchrony in which the dyad is neither overly nor under-coordinated is optimal for socio-emotional development (i.e., 'some is more'; Beebe et al., 2011; Bornstein & Manian, 2013; McFarland et al., 2020). Symmetry observed in the cross-correlation plots (Figure 2 and S1) suggests a generic increase in similarity of caregiver-infant arousal levels, rather than an asymmetric - i.e., caregiver- or infant-led - interaction. Synchronised physiological arousal may reflect similar reactions to various environmental events; for example, a similarly high startle response to a loud noise (Carsten et al., 2023; de Vente et al., 2020). Alternatively, the symmetry could represent a more reciprocal dynamic, implying that caregiver and infant are equally responsive and sensitive to each other’s cues, thus leading to a mutual escalation in dyadic arousal. Clinically, these results may help us conceptualise interventions for perinatal and early childhood anxiety. They suggest that both members of the dyad equally and reciprocally influence arousal levels, highlighting the importance of interventions for perinatal anxiety that, rather than treating caregiver anxiety in isolation, instead support caregivers to recognise and respond to both their own emotional states as well as their infants. The suggestion that both caregiver and infant outcomes may be enhanced by a dyadic approach to perinatal mental health care is coherent with current UK clinical guidelines (which highlight a need to address both symptoms of caregiver psychopathology and the caregiver-infant relationship; NICE, 2014), the findings of a recent systematic review on interventions for perinatal anxiety (Smith et al., 2022), and the outcomes of interest in upcoming perinatal intervention trials (e.g., the COSI trial; Rosan et al., 2023).

An alternative perspective is that perinatal anxiety exerts less of an influence on caregiver-infant dynamics at 5 months than at later ages in infancy, as indicated by research finding weak or no relationships between perinatal anxiety and caregiver-infant physiological synchrony at 5-6 months (Kaitz et al., 2010; Ostlund et al., 2017). Developmental trajectories may underlie this; in the period between 6 and 12 months, infants become more mobile, autonomous, and socially interactive. They are more likely to encounter challenges in the physical environment that place a demand on their self-regulatory processes, e.g., physical obstacles; difficulty grasping something out of reach; falling;

encountering unfamiliar people; separation from primary caregiver. Caregiver-infant interaction dynamics can act as a buffer or amplifier for infant distress in the context of perinatal anxiety (Smith et al., 2023; Smith et al., 2022), perhaps, then, differential arousal dynamics are more likely to be observed in anxious caregivers and their infants as the infant begins to explore the physical environment more actively. This view was supported by patient and public involvement representatives who spoke about experiencing greater vigilance towards their infants' behaviour as their children became more active.[16]

The results regarding the relationship between perinatal anxiety and caregiver-infant synchrony also need to be considered in light of the potentially confounding variable of caregiver mood. Caregivers with postpartum depression are thought to show broadly orthogonal patterns of dyadic interaction to those with postpartum anxiety, such that depressed caregivers show less responsivity and contingency to infant cues (Bernard et al., 2018), less mimicry (Salazar Kämpf & Kanske, 2023), less touch and positive affect (Beebe et al., 2008; Quiñones-Camacho et al., 2023), and less behavioural synchrony (Feldman, 2007b; Granat et al., 2017), as compared with control and anxious caregivers (though see exceptions; Murray, Cooper, et al., 2014). Despite high prevalence of co-occurring perinatal anxiety and depression (Falah-Hassani et al., 2017), it remains unclear to what extent co-occurring depressive symptoms reduce or amplify the effect of perinatal anxiety symptoms on caregiver-infant synchrony. One possibility is that one psychological state will dominate at a given time, and so we will principally see the effect of one condition on dyadic interaction (i.e., either depression or anxiety). This is consistent with recent evidence from Beebe and colleagues, who demonstrated that, in co-occurring perinatal anxiety and depression, some dyads follow depressive dyadic interaction patterns (lowered contingency), and some follow anxious dyadic interaction patterns (heightened contingency; Kahya et al., 2023).

Analyses from the present study also suggested that, across both groups, there was a modest but consistent and significant relationship between synchrony and proximity levels, such that synchrony levels increased as members of the dyad became closer to one another. This is coherent with recent naturalistic research with 4-6 month olds showing that neural synchrony between caregivers and infants was higher when infants were seated on their caregiver's lap instead of next to them (Nguyen et al., 2021), similar to previous lab-based investigations that found stronger autonomic covariation in 12-14 month old infants who sat on their caregivers' laps *vs.* infants not touching their caregiver

[16]Patient and public involvement (PPI) interviews were undertaken with two experts by experience, who reflected on the different forms their anxiety took as their infant developed. When infants were younger, in the pre-crawling stage, perinatal anxiety was described as less intense due to a felt sense of being in control. As infants grew and developed more independence, perinatal anxiety reportedly increased and was focused more on behaviours. In addition, individuals reflected that their heightened perinatal anxiety was related to a quicker and stronger sense of bonding. Experts by experience were involved with perinatal community mental health teams; both were women of working adult age, one from a black British mixed African background and the other from a white British background.

(Waters et al., 2017). Physiological synchronisation may be higher during physical contact due to caregivers' greater opportunity to demonstrate responsivity across multiple modalities at the same time (e.g., touch, spatial orientation, gaze, vocalisations) or due to reciprocal influences of each partner's perception of the other's respiratory and heart rate rhythms (Fairhurst et al., 2014). The present study extends this by demonstrating a relationship between proximity and synchrony among both anxious and non-anxious caregivers and their infants, perhaps indicating that the linkage between physical closeness and physiological synchrony is so fundamental to caregiver-infant interaction that it is less susceptible to variation across emotional states and psychological conditions. This finding may also be relevant for informing targets in parent-infant interventions.

For a subset of the sample, I also explored the relationship between caregiver anxiety, caregiver vocalisations, and caregiver and infant physiological arousal at 10 months. Although preliminary analyses suggested there were no statistically significant differences between overall rates of different types of vocalisations between the low *vs.* moderate anxiety group, results of the linear mixed effects analyses suggested that infant and caregiver arousal change was significantly more likely around instances of caregiver conversational control (e.g., commands/directives, choice questions) when the caregiver's anxiety score was higher. Specifically, I found that higher caregiver anxiety was related to greater infant arousal change around choice questions. Similarly, I observed that higher caregiver anxiety was related to greater caregiver arousal change around times caregivers gave commands. Extant research indicates that maternal stress associates with more commanding child-directed speech (child age 2-6 years; Briscoe et al., 2017), and that directives, imperatives and prompt questions tend to be higher when the parent is less attuned with the child, and less accepting of how the child behaves (child age 2 months to 2 years; Lieven, 1978; Murray & Trevarthen, 1986; Nelson, 1973). The finding of no group differences in overall rate of vocalisations is inconsistent with this, perhaps due to sampling differences between existing and previous research, e.g., differences in infant age or severity of parental stress and anxiety. Differences in age may be especially relevant here, as the function of certain types of questions asked by caregivers may be different in the first year of life compared to later in childhood. For instance, 'what, where, when, how, why' questions - even though they represent caregiver-led initiation and interaction - may function more as descriptive or narrative communication devices, rather than as a mechanism of control.

That there were differences in infant and caregiver stress reactivity to caregiver vocalisations despite no group difference in overall rates of vocalisations suggests that the finding may also reflect differences in the tone or affective context in which words are used, rather than specific words themselves. For instance, caregivers with elevated anxiety traits may use a tone conveying heightened stress, which may trigger greater fluctuation in physiological arousal among infants and caregivers (Smith et al., 2023) irrespective of the words used. Differences in how caregivers respond to infant cues may also increase arousal levels in the dyad; an anxious parent might react more to their own internal heightened arousal and therefore misinterpret their infant's needs (Webb & Ayers, 2015), responding perhaps overly rapidly or intensely, in a way that leads to overstimulation for the infant (Feldman, 2007; Granat et al., 2017; Smith et al., 2023). As such, caregiver anxiety (and subsequent infant reactivity) is perhaps less likely to be observed in the content of vocalisations rather than the structural or acoustic properties of caregiver speech. This fits with evidence demonstrating that caregiver intrusiveness with warmth has a different impact on child socio-emotional outcomes than caregiver intrusiveness in the absence of warmth (Ispa et al., 2004). While substantive missing data precluded analysis of physiological synchrony at the 10-month timepoint in the present study (see Appendix 2), it is also possible that passive processes of stress contagion underlie the above finding, with heightened arousal states in more anxious caregivers automatically transmitting to their infants irrespective of speech patterns.

4.2 General conclusions

Overall, though confirmatory analyses investigating the relationship between perinatal anxiety and caregiver-infant synchrony did not reach significance, sensitivity analyses revealed a pattern of results indicating that anxious caregivers show higher physiological synchrony with their infants at five months. Analyses also showed that synchrony and proximity are positively correlated in both anxious and non-anxious caregivers and their infants, such that caregiver-infant synchrony is higher when infants are closer to their caregivers irrespective of anxiety score. Finally, exploratory analyses on a subset of the sample at 10-months showed that, when caregiver anxiety levels are higher, caregivers and infants experience greater changes in physiological arousal around controlling caregiver vocalisations (e.g., commands/directives, choice questions). Taken together, my findings indicate that alterations in caregiver-infant interaction dynamics can be observed in anxious caregivers and their infants at the behavioural and physiological level, though effects are modest and larger scale studies are needed. The present study also represents a proof-of-concept in the application of novel research methodologies; I have shown that home wearable devices can be used to monitor moment-to-moment physiology and behaviour in perinatal and developmental research, generating insights that can inform future research and practice.

4.2 Limitations

The present study was limited by several factors. Firstly, despite the repeated measures design and high density of data collected per participant, missing data resulted in a smaller than intended overall sample size for the primary analyses, thereby limiting strong inferential claims. However, it is important to note that the conventional power analyses originally employed to estimate the sample size were grounded in assumptions that may not fully address the complexity of time series data (e.g., autocorrelation; lag effects; these complicate estimates of effect sizes).[17] As such, the a priori calculations may not have produced accurate power estimates for analyses concerned with time series data. To mitigate this, sensitivity analyses were conducted extensively on the primary analyses, allowing the consistency of results to be scrutinised under different conditions. By systematically varying key parameters and observing how this impacted on the effects, it was possible to establish the stability of findings across a range of plausible scenarios. Nonetheless, future studies using time series data may benefit from novel statistical procedures for estimating power (Beard et al., 2019; Hawley et al., 2019). Scientists using these analytical procedures can further increase the methodological rigor and scientific integrity of dynamic systems research through public preregistration of the study design, or through pursuing publication as a Registered Report (an innovative publishing format involving peer review before results are known; Chambers & Tzavella, 2021). While the present study was preregistered internally as part of university regulations for doctoral research, the study design was not publicly preregistered or submitted for peer review. This limited opportunities for those within the wider research community to verify the original hypotheses and methods or challenge any potential bias in reporting results.

A further limitation of this study is that the sample was recruited from the community, with the moderate anxiety group including caregivers with mid-range anxiety levels (in a UK context, this would represent those seen by health visitors, IAPT services, and possibly family hubs). Sensitivity analyses suggested that higher GAD-7 scores were associated with higher levels of caregiver-infant arousal cross-correlation, though scores indicative of highly elevated anxiety were relatively under-represented within the sample. Further research with a clinical sample – including perinatal-specific anxiety, depression, and child socio-emotional outcome measures - is necessary to investigate the effects of moderate-to-severe anxiety on relationships of interest. Future research may also benefit from a revision of vocal coding schemes for infants 5-10 months. As discussed above, conceptualisation of specific caregiver vocalisations as ‘intrusive’ (such as choice questions or 'what, where, why, how' questions) without considering the function and tone of these interactions may overlook their descriptive or narrative roles in early communication. Future iterations of vocal coding schemes could include analysis of tone and other acoustic properties, alongside semantic features, to enhance our understanding of the function of specific caregiver vocalisations. As highlighted in recent work (e.g., Dalaet et al., 2024; Law et al., 2021), accurate coding schemes require a detailed approach that integrates both acoustic and contextual factors to avoid misclassification.

Finally, the present study is limited with respect to generalisability. Though the ethnicity of participants for the primary analyses included diverse groups, the majority of participants were

[17]For further detail, see work from Dorais (2024, p. 245): “Determining statistical power is complex with [time series analysis] because determining factors include number of points, sample size of participants, and the autocorrelation of the time points… When the number of data points increases, power increases; conversely, power decreases with an increase in autocorrelation and increases with a larger expected effect size. To date, there is no established form of power analysis [for time series analysis].”

nonetheless from white, Western, and affluent backgrounds, inadequately representing demographic variation both locally and globally. In addition, despite the likely high prevalence of perinatal anxiety and depression among fathers (Leiferman et al., 2021) and caregivers identifying as trans and non-binary (Greenfield & Darwin, 2020), the present study does not include data on gender-diverse caregivers and their infants. This omission perpetuates the marginalisation of these populations in perinatal and developmental research and further highlights issues of external validity (Darwin & Greenfield, 2019). Little, too, is known about how caregiver attitudes to at-home infant monitoring devices vary across different cultural and minoritised groups. Available data in this area has been collected from predominantly white, Western caregivers (Creaser et al., 2022; Fish & Jones, 2021; Prioreschi et al., 2018), limiting our understanding of how acceptable these technologies may be across different communities, and how different attitudes may affect factors impacting on the quality of studies, such as recruitment and attrition. These processes may have influenced the present study, potentially explaining the small and relatively non-diverse sample available for analysis. Future studies need to address issues of under-representation and generalisability as a matter of priority; my research team is actively engaged in these efforts, currently leading a recently funded European consortium that aims to ensure families within developmental research for home wearables are adequately represented across cultures, ethnic groups and nationalities (COST, 2023).

4.3 Clinical relevance: implications for future research and practice

The results of the present study have implications for future research and practice. The work of this thesis is shaped by a focus on the early stage of the research-to-practice translation pathway, i.e., the basic psychological science approach that highlights the importance of understanding mechanisms and processes of developmental psychopathology (Karmiloff-Smith, 1998). By understanding mechanisms of psychopathology, clinician-researchers are better able to develop precise intervention targets. The non-significant albeit consistent pattern of results shown here, regarding how caregiver and 5-month-old infants reciprocally match one another's arousal states depending on the level of caregiver anxiety, contributes to our understanding of how perinatal anxiety may exert an influence on caregiver-infant interaction during the first year of life. Future research will benefit from adequately powered longitudinal studies that allow for an investigation of how early elevated synchrony emerges in anxious dyads. From a clinical and public health perspective, it is important to understand how early elevated synchrony emerges within dyads with an anxious caregiver; doing so will be critical to identifying sensitive periods for children's socio-emotional development as well as for shaping early and preventive interventions. Such research may also help provide context for clinicians navigating the dilemma of how to sequence interventions for caregiver mental health and caregiver-infant interaction (i.e., considering the question of whether caregiver and infant outcomes are more likely to be strengthened if dyadic interaction is targeted after, before, or at the same time, as caregiver mental health).

In addition, the exploratory analyses suggesting a role of caregiver vocal behaviour in both infant and caregiver physiological reactivity highlight how understanding moment-to-moment caregiver-infant interaction dynamics may help to identify mechanisms for caregiver-to-child anxiety transmission. Future clinical research may benefit from a focus on both the content and the structure of anxious caregiver's speech when interacting with their infants, particularly during minor instances of infant negative affect. A focus on this area would help elucidate how core symptoms of anxiety, such as experiential avoidance (an 'unwillingness to remain in contact with private negative experiences, e.g., emotions'; Berman et al., 2010; Fonseca et al., 2018 [p. 2135]), manifest within the perinatal frame. Do caregivers vocally inundate, interrupt, or seek to rapidly distract the infant? How would this compare with a less avoidant caregiver response?

Finally, the methodology of the present study has clinical relevance, raising the question of whether wearable technology could act as an aid during clinical practice. Current parent-infant interventions (e.g., Video Interaction Guidance; Kennedy et al., 2011, 2017) are largely based on short segments of video-taped behavioural observation. Video-based interactive interventions could be enhanced by the use of wearable ECG and audio-visual recording devices in several key ways. Firstly, this equipment would allow for day-long recordings of caregiver-infant dynamics in the home setting. Longer, naturalistic recordings could facilitate capture of spontaneous behaviours that are less likely to be observed in short clinic or lab-based assessments, allowing for more comprehensive assessment of the caregiver-infant dynamic. Secondly, wearable equipment incorporating ECG monitors has the potential to provide real-time bio-feedback, serving as an additional resource during intervention sessions. Possible benefits include helping to externalise interpersonal feedback loops through visualisation of infant and caregivers' heart rate and respiratory patterns, which might be particularly helpful for service users who have difficulty mentalising others or making sense of social interactions through decoding behavioural cues. In video-feedback sessions – which generally show the caregiver in a more optimal interaction pattern (e.g., intruding less than they might at other times) - caregivers may not only learn to psychologically understand their infant, but also to understand how these interaction patterns influence their infant's and their own stress response.

Also of interest is the role of wearable devices in increasing accessibility with regards to the assessment of parent-infant relationships. For instance, for those living in rural areas situated long distances from services, would a wearable ECG monitor and audio-visual recording device allow for greater ease of assessment of the parent-infant relationship? Could the implementation of wearable miniaturised devices, analysed through machine learning models, similarly enhance accessibility to perinatal mental health services, as indicated by the success of other artificial intelligence-enabled tools in increasing diverse groups' access to treatment (Habicht et al., 2024)? For whom would this provision be more or less acceptable (e.g., service users, such as young mothers and birthing people, who indicate a preference for the use of virtual and remote options during treatment, but already feel an ongoing sense of surveillance and evaluation; O'Mahen, 2024)? There is also the question of how interventions are evaluated, and whether it would be beneficial to incorporate physiological outcome measures as part of this (e.g., an index of mid-range physiological synchrony). If physiological measures co-vary with other outcome measures routinely used by clinical services, are they necessary? A mixed methods study, evaluating the feasibility and acceptability of incorporating wearable devices into parent-infant video feedback assessment and intervention, may produce answers to these questions. Co-producing such research with women, birthing people, and their partners will strengthen knowledge of access, experience, and outcomes.

Appendix - Supplementary Materials for: Main Empirical Project

1. Sensitivity analyses for Analysis 2 (5 months): sliding window correlations with CBP test

The below presents the same analyses as Analysis 2, using different lengths for the sliding window of the SWC. The different window lengths do not impact the results, with results showing no differences in concurrent synchrony between low and moderate groups (all *ps* > .025). The negative correlation between synchrony and proximity remains significant across different window lengths (all *ps* < .001), e.g., with a 5 minute window: low anxiety group, rho = -.22, *p* < .001; moderate anxiety group, rho = -.24, *p* < .001.

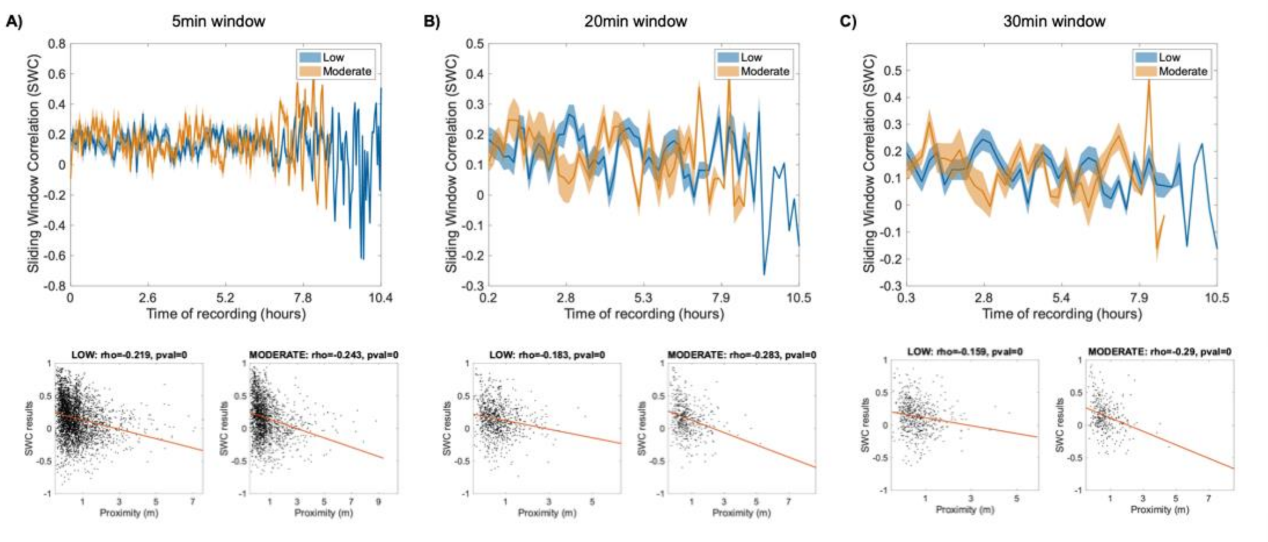

Figure S1. Sensitivity analysis using different window lengths for the SWC: (A) 5 minute window; (B) 20 minute window and (C) 30 minute window. Low anxiety is represented by the blue line (*N* = 36), while moderate anxiety is represented by the orange line (*N* = 21).

The below presents the same analyses, splitting the groups differently (based on bottom *vs.* top 10th percentile).[18] This gave a score of =< 2 for the low anxiety group (N = 16) and => 7 for the moderate anxiety group (N = 12). As above, there were no differences between groups with regard to the SWC. There was a significant negative correlation between synchrony and proximity for the low anxiety group (rho = -.14, $p < .001$) and the moderate anxiety group (rho = -.22, $p < .001$).

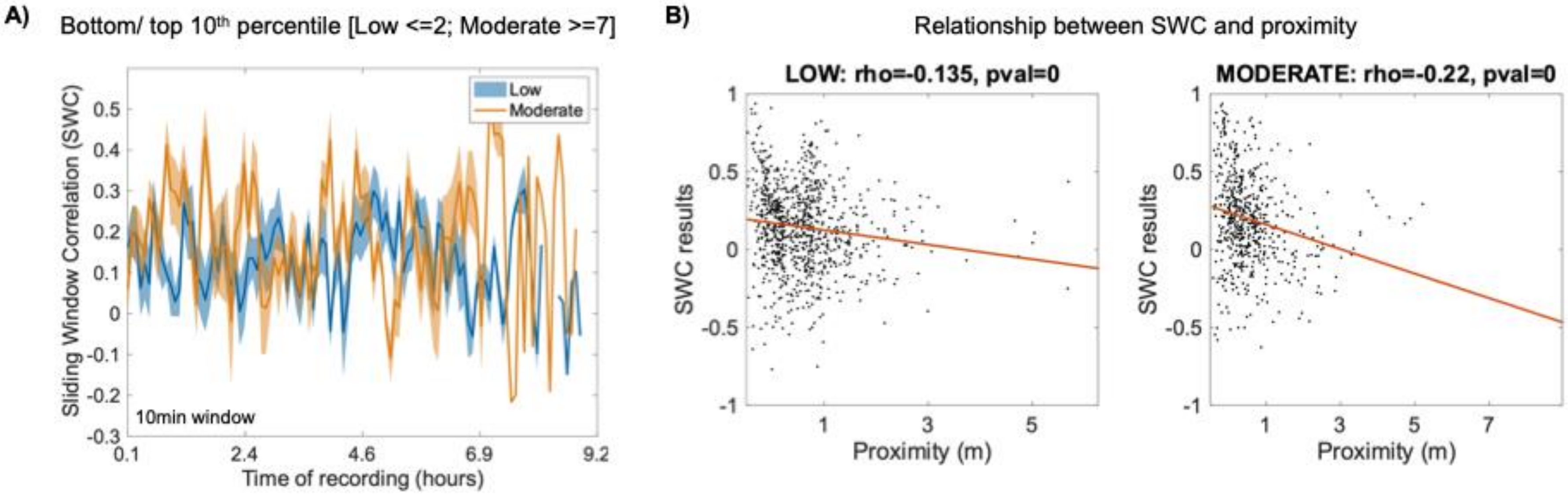

Figure S2. Sensitivity analysis of the SWC based on splitting the groups differently using the top *vs.* bottom 10th percentile. Low anxiety is represented by the blue line (N = 16), while moderate anxiety is represented by the orange line (N = 12).

[18]Though I planned to examine the top *vs.* bottom 20th percentile, this did not allow for meaningful differentiation between low and high poles, hence the 10th percentile was examined as an alternative.

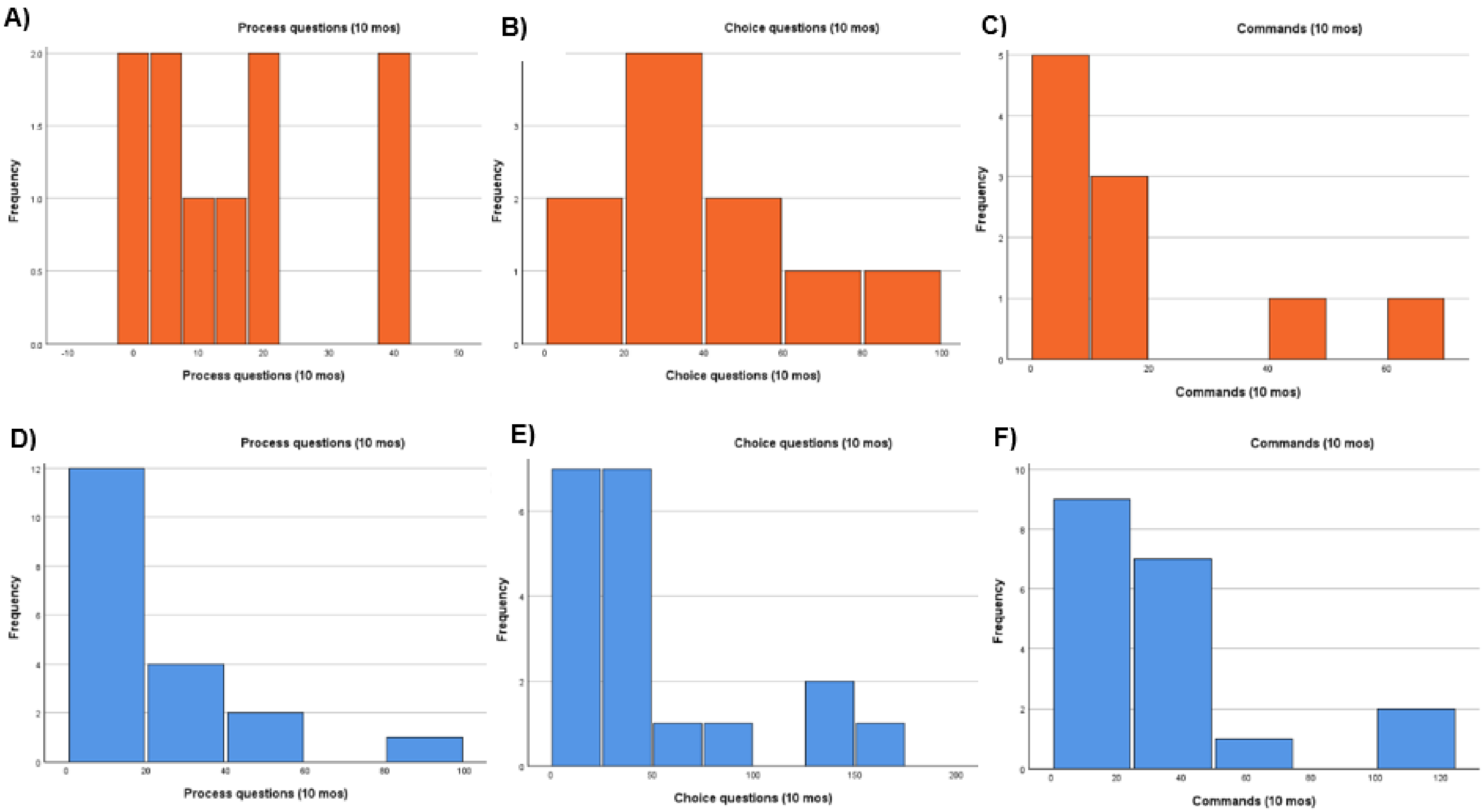

Figure S3. Histograms showing the distribution of different caregiver vocalisation variables per hour, split by group. A-C represent the moderate anxiety group (*N* = 10); D-F represent the low anxiety group (*N* = 21).

Table S1. Demographic characteristics of subgroups that underlie sensitivity analyses, i.e., split by top/bottom 10th percentile (GAD-7 scores ≤ 2 and ≥ 7) and 'extreme' values (GAD-7 scores <2 and >10).

		Bottom/top 10th percentile		Extreme values	
		Low anxiety (N = 16)	Moderate anxiety (N = 12)	Low anxiety (N = 6)	Moderate anxiety (N = 4)
	Infant age (mos) – mean *(SD)*	5.29 (.92)	5.40 (.84)	5.71 (.95)	5.9 (.82)
	Gender (N (%) female)	6 (33.3)	5 (38.5)	2 (22.2)	3 (80)
Infant ethnicity N (%)	White British	7 (38.9)	3 (23.1)	4 (44.4)	1 (20)
	White Other	1 (5.6)	1 (7.7)	1 (11.1)	-
	Afro-Caribbean	-	-	-	-
	South-east Asian	1 (5.6)	-	1 (11.1)	-
	Mixed – White/Afro-Caribbean	-	-	-	-
	Mixed – White/Asian	-	2 (15.4)	-	-
	Other Mixed	2 (11.1)	2 (15.4)	-	1 (20)
Maternal education (%)	Postgraduate	8 (44.4)	1 (7.7)	2 (33.3)	1 (20)
	Undergraduate	2 (11.1)	6 (46.2)	2 (33.3)	1 (20)
	A Level	3 (16.7)	-	2 (33.3)	-
	GCSE	-	1 (7.7)	-	-
	No formal qualification	-	-	-	-
Household income (%)	>£80k	5 (27.8)	5 (38.5)	2 (22.2)	-
	£51-£80k	3 (16.7)	3 (23.1)	2 (22.2)	2 (60)
	£36-51k	1 (5.6)	-	1 (11.1)	-
	<£36	-	-	-	-

For the low anxiety group within the 'top/bottom 10th centile' split, GAD-7 scores ranged between 0 and 2 (*M* = 1.04, *SD* = 0.88), while for the moderate anxiety group, scores ranged between 7 and 16 (*M* = 8.9, *SD* = 2.64). Considering the whole sample of the top/bottom 10th centile split, scores ranged between 0 and 16 (*M* = 4.31, *SD* = 4.34). For the low anxiety group within the 'extreme values' split, scores ranged between 0 and 1 (*M* = 0.41, *SD* = 0.51) while, for the moderate anxiety group, scores ranged between 11 and 16 (*M* = 13, *SD* = 2). For the whole sample of the extreme values split, scores ranged between 0 and 16 (*M* = 3.27, *SD* = 5.48).

2. Missing data and scalability challenges

Of note, the scope of analyses was constrained by several key factors. Firstly, analyses were limited by missing data and the challenge of perfectly aligning three or four distinct datasets (two ECG datasets, maternal vocal recordings, and GAD-7 questionnaire responses), each critical but difficult to synchronise owing to external factors that affected sample size. Missing data may have been related to processes including, but not limited to, equipment issues such as motion artifacts, ECG lead attachment problems, device reliability, inconsistent wearing times, calibration errors and environmental interference. Autonomic data was assumed to be missing completely at random (e.g., due to researcher inconsistency in attaching the ECG leads properly on certain days) or missing not at random (e.g., ECG leads were improperly attached, correlating with the circumstances of the measurement and the condition of the participant at the time). The latter was addressed through use of sensitivity analyses.

In addition, analyses were limited by the organisational and technical context. Datasets were managed by a large research group, with key decision-makers managing competing priorities for processing tasks given diverse team objectives. Analyses were also constrained by the reliance on manual data coding for vocalisation-based analyses. Each hour of data necessitated several days of coding, significantly limiting scalability. In the context of this research, the issue was compounded by the lack of available machine learning techniques that could streamline processes.

3. Marketing materials

References: Main Empirical Project

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