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Mother-child adrenocortical synchrony; Moderation by dyadic relational behavior

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ABSTRACT

Mother-child adrenocortical synchrony, the coupling of cortisol (CT) secretion in mother and child, has been associated with shared parent-child experiences and maladaptive familial contexts. Yet, few studies tested adrenocortical synchrony in diurnal CT patterns. Guided by the bio-behavioral synchrony model, we examined whether mother-child relational behavior and maternal psychopathology may moderate the degree of concordance between mother and child's diurnal CT. Ninety-seven mothers and their six-year old children participated in two groups; mothers diagnosed with major depression disorder (N = 28) and non-depressed controls (N = 69). Mother-child interactions were observed and coded for dyadic reciprocity and dyadic tension and diurnal cortisol was collected from mother and child over two consecutive weekend days. Concordance between maternal and child's diurnal CT was found, significant above and beyond time of measurement. Maternal depression, while associated with attenuated child diurnal CT variability, was unrelated to adrenocortical synchrony. Higher child diurnal CT production predicted a stronger linkage between maternal and child's diurnal CT, suggesting that greater child physiological stress is associated with increased susceptibility to the influences of maternal stress physiology. Mother-child reciprocity was related to lower adrenocortical synchrony. Findings suggest that higher adrenocortical synchrony is associated with greater physiological stress and less adaptive dyadic relational patterns. Results raise the possibility that diurnal adrenocortical synchrony taps a unique aspect of HPA-axis functioning whose role in the cross-generational transfer of stress physiology requires further research.

1. Introduction

Cumulative evidence indicates that production patterns of the hypothalamic-pituitary-adrenal (HPA) axis hormone cortisol (CT) are coordinated between mother and child, and studies employed a variety of terms to describe this phenomenon, such as cortisol coregulation, hormonal concordance, stress contagion, or adrenocortical synchrony (Atkinson et al., 2013; Mörelius et al., 2015; Papp et al., 2009; Ruttle et al., 2011; Saxbe et al., 2014; Stenius et al., 2008). Most studies assessing mother-child CT concordance examined the coordination of CT following stress manipulations and found that when stress is experimentally elevated in either mother or child both partners increase CT levels in a coordinated fashion (Atkinson et al., 2013; Hibel et al., 2015; Mörelius et al., 2012, 2009; Neu et al., 2009; Ruttle et al., 2011; Sethre-Hofstad et al., 2002). In contrast, very few studies focused on the coordination of diurnal CT patterns between mother and child (Hibel et al., 2014; LeMoult et al., 2015; Papp et al., 2009; Schreiber et al., 2006; Stenius et al., 2008; Williams et al., 2013), a distinct aspect of HPA-axis functioning that is often uncorrelated with CT reactivity to momentary stressors (Edwards et al., 2001). As such, the mechanisms underlying mother-child diurnal CT concordance are largely unknown, particularly since this form of concordance may be associated with different factors from those linked with the coordination of phasic CT response. Since the consolidation of diurnal CT plays an important role in the development of children's stress response and aberrant diurnal CT patterns in childhood increase the risk for later psychopathology (Gunnar and Vazquez, 2001; Hart et al., 2009; Hastings et al., 2011), shedding further light on mother-child diurnal CT coordination may be of conceptual and clinical importance.

Several mechanisms may underpin the linkage between maternal and child's diurnal CT patterns, including genetic dispositions, shared environment, and learned behavior. One such pathway is charted by the *bio-behavioral synchrony* model, which posits that coordination between parent's and child's biological processes develops through online coordination of social behavior during moments of social contact

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(Feldman, 2016, 2007a). Bio-behavioral synchrony is a key feature of mammalian development that enables parent and young to mutually adjust physiological and social signals, permits the parent's mature physiological systems to externally-regulate the infant's immature systems, and provides an evolutionarily-adaptive mechanism to sensitize young to challenges in their environment (Feldman, 2015a, 2015b, 2012a, 2012b; Hofer, 1995; Stern, 1977). Research has shown that maternal physiological and behavioral systems dynamically adapt to the child's state, degree of system maturity, and ongoing risk signals from the environment and respond online to the infant's social cues (Feldman, 2015a; Hofer, 1995; Mogi et al., 2011). Similarly, studies have indicated that moments of mother-child behavioral synchrony are related to concordance in physiological systems, such as coupling of heart rhythms between mother and child (Feldman et al., 2011) or coordinated release of oxytocin (Feldman et al., 2010a). It is thus possible that adrenocortical synchrony in diurnal patterns may develop on the basis of cumulative moments of hormonal concordance when mother and child's CT production has been adjusted to fit the partner's current state. This hypothesis is supported by research indicating that diurnal CT concordance within the family correlates with the amount of shared experience (Mörelius et al., 2012, 2015; Schreiber et al., 2006; Stenius et al., 2008). For instance, preterm infants placed in family care and exposed to maternal-infant skin-to-skin contact exhibited CT concordance, while no correlations in CT were found among infants placed in standard incubator care (Mörelius et al., 2012, 2015). Six-month-old infants showed greater diurnal adrenocortical synchrony with their mothers as compared to their fathers (Stenius et al., 2008); in preschool-aged children mother-child morning CT levels were synchronized only on non-work days (Hibel et al., 2014); and among adolescents shared environment was a better predictor of afternoon CT linkage than genetic factors (Schreiber et al., 2006).

Differences in the amount of shared experience per se may not be sufficient to explain variability in adrenocortical synchrony, as mother-child pairs vary not only in hormonal linkage but also in the behavioral aspects of their relationship. The mother-child relationship is a central contributor to the development of children's HPA-axis functioning (Albers et al., 2008; Brummelte et al., 2011; Feldman et al., 2010b; Tu et al., 2007) and, thus, CT linkage may be related to the amount of reciprocal social interactions between mother and child. Studies in rodents indicate that the mother's species-adaptive behavior carries a unique effect on the consolidation of the pup's HPA reactivity, above and beyond the effects of nursing and maternal presence (Gubernick and Alberts, 1983; Rosenberg et al., 1970). Mothers with low corticosterone levels displayed more maternal behavior and their infants showed lower HPA-axis reactivity in adulthood (Francis and Meaney, 1999; Liu et al., 1997). Cross-fostering studies showed that maternal behavior exerted epigenetic effects on the pup's neural and behavioral response to stress, and these effects were found to override the effects of genetic dispositions (Champagne and Meaney, 2001; Kundakovic and Champagne, 2015). These findings not only provide evidence for the concordance between maternal and child's HPA-axis functioning and its lifetime implications but also suggest that variability in maternal caregiving may play a role in adrenocortical synchrony (Macrì et al., 2011).

Mother-child adrenocortical synchrony is a systemic construct; hence, at the behavioral level one should look for systemic features of the dyadic functioning as correlates. Two systemic constructs have been employed to define the dyadic atmosphere – dyadic reciprocity and dyadic negativity/tension – and both address the nature of the relationship rather than the behavior of one partner or the other. Dyadic reciprocity indexes the degree of coordination, synchrony, and mutual responsiveness in the mother-child system, whereas dyadic tension describes a relationship marked by heightened vigilance, negative effect, and anxiety. Longitudinal studies have shown that both styles are individually stable from infancy to adolescence (Feldman, 2010; Feldman et al., 2013a; Kochanska and Murray, 2000; Stright et al., 2008), suggesting that their associations with the child's HPA-axis functioning may relate to their consistency over time. Dyadic reciprocity has been associated with better vagal regulation during the still-face paradigm (MacLean et al., 2014; Moore and Calkins, 2004; Pratt et al., 2015), and more adaptive CT response to challenges in mother and child (Feldman et al., 2013b). Dyadic negativity/tension has been linked with poor emotion regulation (Cabrera et al., 2007), heightened CT response to stress, and lower CT variability (Albers et al., 2008; Brummelte et al., 2011; Feldman et al., 2010b; Tu et al., 2007).

Despite evidence showing that dyadic reciprocity and dyadic tension are associated with children's CT levels (Albers et al., 2008; Feldman et al., 2013b), no study, to our knowledge, examined their links with concordance in diurnal CT patterns. Studies assessing the relationship between maternal and family characteristics and the degree of mother-child CT linkage yielded mixed results. Some studies showed that sensitive mothers exhibit greater CT linkage with their children following induced stress (Atkinson et al., 2013; Hibel et al., 2015; Ruttle et al., 2011; Sethre-Hofstad et al., 2002). Others have shown that higher adrenocortical synchrony is observed in families with higher levels of maladaptive relationship patterns, such as partner violence and punitive parenting (Hibel et al., 2009), more negative affect between mother and child (Papp et al., 2009), and lower affective involvement within the relationship (Williams et al., 2013). Thus, the associations between mother-child interaction patterns and CT linkage are still not fully clear. One possible explanation may relate to the context in which CT linkage occurs. When individuals face external stressors that require immediate fight-or-flight response, mother-child CT linkage can be an adaptive mechanism aimed to signal danger to the child in a non-verbal manner. However, when the source of stress stems from intra-familial factors, higher adrenocortical synchrony may index over-activation of the *bio-behavioral synchrony* mechanism and may disrupt the mother's ability to soothe the child by reducing the linkage between her own stress response and that of the child's. Thus, dyads in which mother displays higher levels of the species-adaptive behavior may exhibit higher adrenocortical synchrony to acute external stressors but lower synchrony in daily CT production.

An additional factor potentially associated with adrenocortical synchrony is maternal psychopathology. In the presence of maternal stress-related psychopathology, synchronization of the stress response may induce vulnerability via the cross-generational transfer of stress physiology (Gunnar and Quevedo, 2007; McEwen, 1998). Studies have shown that when mothers employ maladaptive mechanisms for handling stress, the same non-optimal mechanisms are found in their children (Badanes et al., 2011; Bartels et al., 2003; LeMoult et al., 2015; Williams et al., 2013). One psychopathology that may be of interest in this context is maternal depression. Maternal depression has been associated with altered maternal CT patterns, including higher basal CT and reduced diurnal variability (Burke et al., 2005; Hankin et al., 2010). Exposure to maternal depression alters children's HPA-axis functioning and children of depressed mothers display higher basal CT levels (Brennan et al., 2008; Feldman et al., 2009; Halligan et al., 2004; Murray et al., 2010) and lower diurnal and reactive CT variability (Apter-Levi et al., 2016; O'Donnell et al., 2013), especially when maternal depression co-occurs with other risk factors (Badanes et al., 2011; Velders et al., 2012), such as greater dyadic negativity/tension and lower reciprocity (Apter-Levi et al., 2016; Feldman et al., 2009; Murray et al., 2010). Diurnal adrenocortical synchrony was found in mother-daughter pairs when the mothers were depressed (LeMoult et al., 2015), and CT linkage following a stressor was tighter between depressed mothers and their infants compared to controls (Laurent et al., 2011). Importantly, studies assessing the timing of maternal depression indicate that early (Essex et al., 2001) and chronic (Barker, 2013) depression pose the greatest risk.

As such, the current study assessed whether maternal depression and mother-child dyadic relational behavior moderate the degree of concordance between maternal and child's diurnal CT. We examined

concordance in diurnal CT between mothers and their six-year old children in two groups; mothers diagnosed with major depression and non-depressed controls. We chose to focus on the preschool stage as it is the time when diurnal CT patterns first consolidate (Gunnar and Donzella, 2002), yet this period received little empirical attention. The preschool years mark a sensitive period for the developmental of stress resilience and preschoolers' CT is still highly sensitive to mother-child interaction (Gunnar and Donzella, 2002). Consistent with previous findings (Albers et al., 2008; Brummelte et al., 2011; Feldman et al., 2013b; Tu et al., 2007) we measured two dyad-level constructs - reciprocity and tension.

Three hypotheses were proposed. First, we expected to find adrenocortical synchrony in diurnal CT patterns between mothers and their six-year-old children. Second, we tested whether maternal depression would moderate this CT linkage in preschool-aged children. Previous studies yielded mixed findings, with maternal postpartum depression predicting stronger linkage in infancy (Laurent et al., 2011) and remitted depression showing no effect in adolescence (LeMoult et al., 2015); thus, associations with maternal depression at the preschool stage remained a research question. Finally, we expected mother-child dyadic relational patterns – reciprocity and tension – to moderate the degree of adrenocortical synchrony. Specifically, in light of research linking maladaptive relational patterns within the family to higher mother-child adrenocortical synchrony (Hibel et al., 2009; Papp et al., 2009; Williams et al., 2013), we hypothesized that when relationships are less reciprocal and more tense, linkage between mother and child's diurnal CT secretion would be higher.

2. Methods

2.1. Subjects

The initial cohort included 1983 women who were recruited on the second postpartum day in three maternity wards. To avoid the confounding effect of comorbid conditions that independently affect maternal behavior and the CT system, we recruited only mothers who were healthy, completed high school, were at least 21 years old, above poverty cutoff, were married or cohabitating with the child's father, and whose infants were born at term and were healthy and singleton.

Women with Beck Depression Inventory (BDI; Beck et al., 1961) scores in the high (BDI scores > 11) end of the depressive symptoms continuum at birth were recruited for the depressed group, and women in the low (BDI < 8) end of the depressive symptoms continuum at birth were recruited for the non-depressed group. Both groups were asked to complete measures of anxiety and depression at 6 months (900 were approached and 680 responded, 76% with no differences in rates of response among the two groups) and again at 9 months (350 were approached and 254 responded, 73% with no difference in response among groups), eliminating mothers with mid-level depression scores (9 < BDI < 11) between these two stages. This additional assessment was done in order to ascertain that mothers in the depressed group still showed elevated symptoms of depression at 9 months postpartum and mothers in the control group did not exhibit elevated symptoms at any point throughout the first nine months of the infant's life. Between these two stages women with high levels of anxiety symptoms (State-trait Anxiety Inventory score above 43; Spielberger et al., 1970) were excluded, since mothers with anxiety and depression were found to display different patterns of maternal behavior and the focus of this study was on the bio-behavioral correlates of maternal depression. Of the responding mothers at 9 months, 192 (76%) were clinically diagnosed and observed. Of these women's families, 156 (81%) were visited when the child was 6 years old and attrition was due to inability to reach the families, unwillingness to further participate, and elimination of families in which mothers had comorbid disorders at 9 months. Seven mothers with comorbid disorders such as anxiety and eating disorders were excluded from the sample. This led to a final cohort of 149 families; 46 chronically depressed women and 103 controls. Control women showed no elevated depression or anxiety symptoms across the first year and were free of any clinical diagnosis at 9 months and at 6 years. Due to insufficient funding to measure diurnal CT from the entire sample (24 samples for each family) we chose a random, sufficiently large cohort of 97 subjects (69 families from control group and 28 families from depressed group) for diurnal collection of CT. At the six years assessment, children's age was 6.33 years (SD = 1.25), mother's age was 38.66 years (SD = 4.40), and father's age was 41.04 years (SD = 4.74). Eighty percent of the parents had college degrees, 91% were married, and 89% of the mothers were employed. Among the children, 51% were boys and 36% were the firstborn. Of the mothers diagnosed with depression, two (4%) were treated with medication, and four depressed mothers (9%) and 10 comparison mothers (10%) received psychotherapy, with no effect on any maternal or child measurements.

The study was approved by the IRB. Procedures were explained to the adult participants before the beginning of the study and all signed informed consent. Parents received a gift certificate for participation.

2.2. Procedure and measures

Families were visited at home in the afternoon hours (after 1500 h) and visits were conducted by two clinical psychologists. After explaining the procedure, mother and child were separated into two rooms, mothers were administered the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-I; First et al., 1997) while the child was administered several tests and social paradigms. Following, mother and child were videotaped in a ten-minute interaction with age-appropriate pre-selected toys. At the end of the visit mothers were given salivates and instructions for diurnal salivary sampling of CT.

2.2.1. Beck Depression Inventory

Beck Depression Inventory (Beck et al., 1961) was measured at birth, 6, and 9 months. This 21-item self-report inventory is designed to measure the severity of depressive symptoms. Scores of above 9 indicate elevated depressive symptoms and a risk for MDD.

2.2.2. State-trait Anxiety Inventory

State-trait Anxiety Inventory (Spielberger et al., 1970) was used at birth, 6, and 9 months. This instrument examines transitory anxiety states and stable propensity for anxiety. The trait anxiety score was used. Scores of 43 or above are considered a risk indicator for anxiety disorders.

2.2.3. Maternal psychiatric diagnosis

Maternal Psychiatric Diagnosis – was conducted at both nine months and six years using the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-I; First et al., 1997). Forty-six mothers (29.6%) were defined as chronically-depressed. These mothers showed high depressive symptoms (BDI > 11) at birth, six, and nine months, received a clinical diagnosis of MDD at both nine months and six years, and reported being depressed throughout most of the child's first six years. The control group included 103 mothers (66%), who did not show elevated symptoms of depression and anxiety across the first nine months and had no Axis-I diagnosis at both 9 months and six years.

2.2.4. Hormone collection and analysis

2.2.4.1. Diurnal cortisol collection. Due to the episodic secretion pattern of steroid hormones, we can expect reproducible and reliable results in cases of multiple sampling. Consistent with prior research (Liu et al., 2013; Stenius et al., 2008), we thus instructed mothers and children to give 6 samples each, three on each day for two consecutive days as follows; (a) at awakening, prior to eating, drinking, or brushing teeth, (b) at noon time before eating lunch, and (c) immediately before

going to bed prior to teeth brushing. The saliva collection method was by unstimulated passive drool. Samples were stored at −20 °C until analysis. Mothers kept a log of the exact time of measurements in both of the sampling days. Mean time of collection for children was 7:51 h for morning samples (SD = 37 min), 13:42 h for noon samples (SD = 36 min), and 20:13 h for evening samples (SD = 49 min). Mean time of collection for mothers was 7:49 h for morning samples (SD = 43 min), 13:43 h for noon samples (SD = 35 min), and 20:44 h for evening samples (SD = 70 min).

2.2.4.2. Cortisol analysis. In order to precipitate the mucus, samples underwent three freeze-thaw cycles, freeze at −70 °C and thaw at 4 °C. After the forth cycle the tubes were centrifuged at 1500*g* (3000 rpm) for 30 min. Supernatants were divided to aliquots and stored at −20 °C until assayed. Cortisol levels were assayed using a commercial ELISA kit (Assay Design; MI, USA). CT levels were calculated by using MatLab-7 according to relevant standard curves. The intra-assay and inter-assay coefficients were <10.5 and 13.4%, respectively.

2.2.5. Mother-child interaction

Ten minutes of mother-child interactions with a set of pre-selected toys were filmed (Feldman, 2007b). Interactions were coded with the Coding Interactive Behavior (CIB) manual, a well-validated global system of 45 codes which are aggregated into several constructs that has been used extensively in research of typical and high-risk parent-child dyads across multiple ages and cultures (for review, Feldman, 2012b). Two coders, trained to 85% reliability on all codes and blind to all other information, coded the interactions. Inter-rater reliability was computed for 20% of the interactions and reliability was >87% on all codes (intra-class r = 0.88–0.96). The *Dyadic Reciprocity* and *Dyadic Tension* constructs were used here. Each scale included in the constructs is coded on a scale from 1 (minimal expression of the target behavior during the interaction) to 5 (maximal expression of the target behavior during the interaction) and scales are averaged to create the final construct consistent with much prior research (for review, see Feldman, 2012c).

Dyadic Reciprocity – describes the degree in which mother and child are involved in a "give-and-take" interaction and participate in joint activity, the interaction is fluent and mutually-adaptive and parent is focused on the child and encouraging him.

Dyadic Tension – represents the degree in which the mother-child interaction is colored by mutual negative affect, anger, hostility, and heightened vigilance.

2.3. Statistical analysis

Prior to analysis, missing values were imputed by regression (<10% of the cases in each variable) and extreme values were explored. One family from the control group in which child morning CT was >4 SD above average was excluded from further analysis. Following, independent sample *t*-tests were computed to examine differences in study variables between the two groups and Pearson correlations were tested between all study variables.

To examine our hypotheses, multilevel modeling (HLM 7.0; Raudenbush et al., 2011) was used to test mother-child diurnal cortisol synchrony. This approach is well-suited for data with a nested structure, such as multiple cortisol sampling occasions nested within participants. We first examined the effects of day and time of measurement. For that end, we entered the data in three levels; at level 1, we included all cortisol data from mothers and children (6 measurements) and a time-point variable was entered to control for diurnal variation in CT (coded as 1, 2, or 3 for the first, second and third sample). At level 2, we included the day of measurement (coded as 1 or 2). At level 3, we included the measurements tested at the dyadic level, that is, group (depressed versus non-depressed) and mother-child interaction measurements (*Dyadic Reciprocity* and *Dyadic Tension*).

As a preliminary step, we first ran the model without moderators to assess the effect of time and day of measurement, and dyadic differences on the variation in mother and child CT measurements. Diurnal variation accounted for 95.24% of the variation in maternal CT and 97.7% of the variation in child CT. The day of CT measurement accounted for 0.09% of the variance in maternal CT and 0.11% of the variance in child CT, hence we decided to collapse the model to two-level HLM, averaging the day across the CT measurements at the three time-points. Finally, individual differences between dyads accounted for 4.67% of the variance in maternal CT and 2.19% of the variance in child CT.

We then ran a two-level HLM model, in order to test our hypotheses, predicting child cortisol from time-point (1, 2, or 3) and from parent cortisol (at the same time-point), and entering the dyadic measurements as moderators of the correlation between mother and child cortisol measurements on the second level.

3. Results

Prior to hypothesis-testing, we present group differences in demographic variables in Table 1. As seen, no significant difference was found between the depressed and control groups in any demographic factor.

3.1. Preliminary analysis

Means and standard deviations for all study variables in the two study groups are presented in Table 2. In order to examine individual differences in CT levels we calculated two measurements that are frequently used in CT research which represent mean and variability of CT in mothers and children across the day; area under the curve with respect to ground (AUCg) and area under the curve with respect to increase (AUCi) (Pruessner et al., 2003). The AUCg is an estimate of total diurnal CT secretion over the six measurements (3 times a day, for two consecutive days: morning, noon and evening). The AUCi is a measure of the dynamic decrease in diurnal secretion, associated with the variability and sensitivity of the system and indexing change across the day.

Differences related to maternal depression were measured by a series of *t*-tests (Table 2). Graphic presentations of group differences in child CT secretion are displayed in Fig. 1. Children of depressed mothers showed a smaller decline in diurnal CT levels compared to children of non-depressed mothers as expressed by a significant group difference in children's AUCi. Mother-child *Dyadic Reciprocity* was lower in dyads comprised of a depressed mother and her child compared to non-depressed mothers-child dyads.

Correlation matrix between all study variables is presented in Table 3.

3.2. Dyadic diurnal adrenocortical synchrony

The two-level HLM model predicting child CT from mother CT showed that maternal CT across the three measurements was

Table 1
Demographics information for depressed and non-depressed groups.

	Non-depressed		Depressed		Statistics
	Mean	SD	Mean	SD	T value
Mother education	14.24	2.54	13.97	2.78	0.54, ns
Mother age (years)	37.05	4.12	35.74	4.9	1.76, ns
Father education	13.42	3.24	13.93	2.56	0.88, ns
Father age (years)	39.7	4.56	37.96	5.5	1.51, ns
Child age (months)	76.51	14.69	71.33	13.46	1.84, ns
Child gender					$\chi^2(1) = 0.25$, ns
Male %	52.7%		57.5%		54.2%
Child birth order					$\chi^2(1) = 3.50$, ns
Firstborn %	36.2%		54.1%		41.1%

Table 2
Means and SDs of the study variables in the depressed and non-depressed groups.

	Non-depressed		Depressed			
	Mean	SD	Mean	SD	T value	Cohen's d
Mother-child dyadic reciprocity	3.64	0.56	3.31	0.71	2.42*	0.51
Mother-child dyadic tension	3.44	0.47	3.42	0.36	0.19	0.04
Child CT AUCg nmol/L	47.51	9.96	51.64	15.64	−1.78	0.37
Child CT AUCi nmol/L	−25.21	18.99	−17.36	13.44	−2.23*	0.38
Mother CT AUCg nmol/L	59.78	14.44	57.74	10.49	0.76	0.02
Mother CT AUCi nmol/L	−35.37	22.25	−30.92	18.29	−1.05	0.32

* $p < 0.05$.

significant in predicting child CT above and beyond the effect of diurnal variation ($b = 0.31$, $t(96) = 5.23$, $p < 0.001$).

3.3. Moderating effects on adrenocortical synchrony

Prior to testing the hypothesized moderation effects on adrenocortical synchrony, we examined whether confounding variables were significant moderates of the linkage between mother and child's diurnal CT. This was done in order to evaluate whether these factors need to be controlled in later analyses. For this goal, we tested two-level HLM models in which we entered maternal and child CT measurements at the three time-points and the time variable at the first level and the possible confounders at the second level. We set child CT as the outcome variable and mother CT and time as predictors and examined whether the confounding variables moderated the effect of mother CT on child CT. None of the confounding variables, including maternal age ($b = -0.01$, $t = -1.59$, NS), child age ($b = 0.002$, $t = 0.84$, NS), child gender ($b = -0.04$, $t = -0.45$, NS), and maternal education ($b = 0.0001$, $t = 0.004$, NS) were found to be significant moderators of mother-child adrenocortical synchrony and were therefore not included in further analyses.

To test the moderating effects of maternal depression and mother-child dyadic interaction variables on mother-child CT linkage, we ran two models. In each model, we entered maternal depression and one of the interaction behaviors (*mother-child dyadic reciprocity*, *mother-child dyadic tension*), as moderators of the effect of maternal CT on child CT. Results are presented in Table 4. As can be seen, maternal depression was not found to moderate CT linkage. Mother-child *dyadic reciprocity* showed a significant negative moderating effect, indicating that the more *dyadic reciprocity* was observed in the mother-child interaction the less mother and child's diurnal CT were coupled.

While testing the models, it became evident that the intercept (i.e. the mean child diurnal CT secretion) and the predictor (i.e. the correlation between mother and child diurnal CT) were highly correlated ($r = 0.997$). We thus examined the significance of this effect. For this end, we ran another two-level HLM model entering the standardized CT measurements in the mother and the child and the time variable in the first level, and the standard mean diurnal CT of the child at the second level. Child mean diurnal CT emerged as a moderator of the correlation between mother and child"s CT ($b = 0.22$, $t = 4.93$, $p < 0.001$). This suggests that the greater the child's CT secretion throughout the day, the stronger the linkage between maternal and child's diurnal CT.

4. Discussion

Evidence suggests that the coordination of CT secretion within affiliative bonds is associated with shared environment and common daily experiences (Mörelius et al., 2012, 2015; Schreiber et al., 2006; Stenius et al., 2008), yet the mechanisms that support coordination of diurnal patterns are largely unknown. Since the development of adaptive diurnal CT is essential for children's health and well-being (Gunnar and Vazquez, 2001; Hankin et al., 2010; Shirtcliff et al., 2012), our goal was to examine mother-child linkage in diurnal CT and assess its relational correlates. Our findings clearly demonstrate coordination between maternal and child's diurnal CT production at the preschool stage, which was significant above and beyond time of measurement. We also found that mother-child dyadic reciprocity moderated the degree of diurnal CT linkage, with children growing in the context of higher reciprocity displaying less tightly-coupled diurnal patterns. Furthermore, as children increased the amount of diurnal CT secretion, mother-child linkage became tighter, suggesting that greater child physiological stress is associated with increased susceptibility to the influences of maternal stress physiology. Finally, while children of depressed mothers showed attenuated diurnal CT decline, no difference in CT linkage was found between depressed and non-depressed dyads, suggesting that adrenocortical synchrony taps a distinct aspect of HPA-axis functioning than that indexed by a host of previously researched measures of CT in the individual. Overall, our findings point to child stress and mother-child interaction patterns as moderators of adrenocortical synchrony and suggest that in the context of lower reciprocity and increased physiological stress, CT linkage becomes tighter. It is important to note, however, that our findings are correlational and no causal effects can be inferred.

Consistent with prior research (LeMoult et al., 2015; Papp et al., 2009; Stenius et al., 2008; Williams et al., 2013), we found that maternal CT was associated with child CT levels across the day even after controlling for time of measurement. Studies in infants showed that parent-

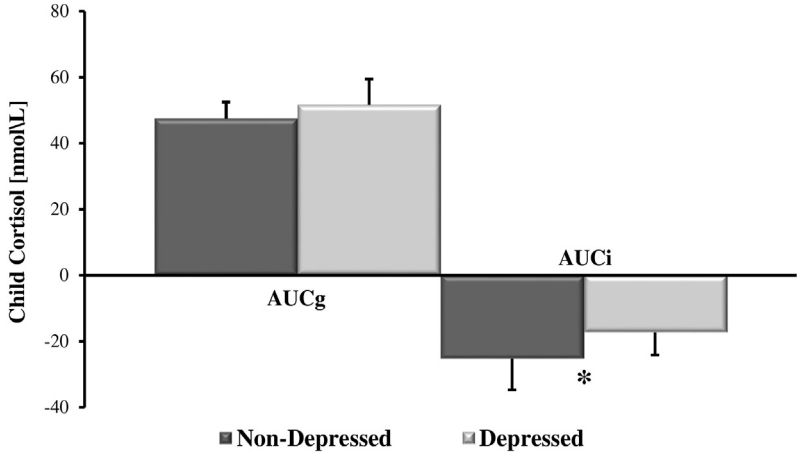

Fig. 1. Group differences in children's CT levels.

Table 3
Pearson correlations between all study variable.

	Mother-child dyadic tension	Child CT AUCg nmol/L	Child CT AUCi nmol/L	Mother CT AUCg nmol/L	Mother CT AUCi nmol/L
Mother-child dyadic reciprocity	−0.47**	0.05	−0.04	0.09	−0.09
Mother-child dyadic tension		0.11	−0.04	0.05	−0.11
Child CT AUCg nmol/L			−0.29*	0.37**	−0.18
Child CT AUCi nmol/L				−0.28*	0.32**
Mother CT AUCg nmol/L					−0.66**

* $p < 0.01$.
** $p < 0.001$.

child adrenocortical synchrony was significant only when parent and child spent a significant amount of time together (Mörelius et al., 2012, 2015; Stenius et al., 2008). During the preschool years, all studies found significant correlations in CT levels between all family members and such concordance was found both following external stressors (Ruttle et al., 2011; Saxbe et al., 2014) and in diurnal patterns (Papp et al., 2009; Schreiber et al., 2006; Williams et al., 2013). It thus appears that by the preschool stage, children have accumulated a sufficient amount of shared experiences within the family context across a variety of stressful and daily situations to facilitate adrenocortical synchrony.

It is speculated that the development of mother-child adrenocortical synchrony begins prenatally; maternal CT during pregnancy was found to account for approximately 30% of the variability in fetal CT concentrations (Gitau et al., 2001), and studies assessing the relationship between maternal prenatal CT and infant postpartum CT levels found that higher maternal morning and afternoon CT predicted greater infant CT reactivity and poor recovery from stressors (Davis et al., 2011; Gutteling et al., 2004, 2005). During the postpartum period, coordination between mother and child's CT is maintained by the continuous synchrony of mother and child's biological and behavioral processes (Feldman, 2012a, 2012b, 2006). Furthermore, the way mother reacts to external stressors is associated with infant stress reactivity (Mörelius et al., 2012, 2009; Neu et al., 2009; Waters et al., 2014) and it is thought that mothers provide the context for the interpretation of stressful experiences (Feldman et al., 2013b). As children grow and their stress-response systems stabilize, it is possible that patterns which are repeatedly reinforced during mother-child interactions may contribute to the consolidation of the stress response (Gunnar and Donzella, 2002). The fact that the moderation effects found here were relatively mild may suggest that as children grow and form meaningful relationships outside the family, the effects of maternal behavior may decrease in magnitude (Gunnar and Donzella, 2002). Thus, much further research is required to test the moderating role of mother-child relational patterns at different time-points across development.

Importantly, the effect of maternal CT on infant CT reactivity is thought to have an important role in preparing offspring to their ecological niche by signaling to the developing stress system that the environment is dangerous and high vigilance is required (Sandman et al., 2012). This preparation, however, comes at cost. Two recent reviews on the effects of maternal prenatal CT on children's developmental outcomes indicate that high CT, especially in the third trimester, is associated with more health problems, lower cognitive functioning, alterations in brain development, and higher emotional reactivity in offspring (Sandman et al., 2012; Zijlmans et al., 2015). Furthermore, infants exposed to high maternal CT who developed high CT reactivity were at greater risk for multiple types of psychopathology throughout life (Essex et al., 2011; Feldman et al., 2013b; Hastings et al., 2011). These findings may chart a pathway of stress contagion between mother and offspring; mothers high in stress physiology during pregnancy deliver newborns with higher stress reactivity, which in turn may up-regulate maternal CT secretion and mother-child adrenocortical synchrony. This is consistent with our finding which showed that higher child diurnal CT was related to greater mother-child adrenocortical synchrony, indicating that tighter diurnal CT concordance may index maladaptive child stress response mechanisms involving increased vigilance. While this mechanism can be adaptive in childrearing contexts marked by increased danger, it may lead to vulnerability when the mother's stress-response systems are over-vigilant.

In the same vein, our findings indicate that when mother-child interaction patterns are less adaptive, mother-child diurnal CT secretion show greater synchrony. This finding is contrary to research showing that maternal sensitivity is associated with higher mother-child CT linkage following stress manipulation (Atkinson et al., 2013; Hibel et al., 2015; Ruttle et al., 2011; Sethre-Hofstad et al., 2002). Two main differences in empirical design may explain these contradictory results. First, these studies tested children of healthy mothers; and second, they examined CT linkage following stress manipulation and not diurnal patterns. It is possible that linkage in CT reactivity to external stressors may be a feature of adaptive relationships, where mothers prepare their children to stressful experiences and help regulate their momentary stress. In contrast, diurnal CT synchrony may be more sensitive to ongoing relational stress and thus heightened concordance may emerge in contexts where mother up-regulates the child's stress response, creating a stress-contagion cycle instead of downregulating the child's distress.

Overall, findings contribute to the *bio-behavioral synchrony* model (Feldman, 2012a, 2016) by emphasizing that in some cases greater biological synchrony does not necessarily imply better child outcomes and biological attunement should be examined from a system-specific perspective. Interestingly, with regards to behavioral synchrony, evidence also suggests that extra-tight coupling may not always be optimal. Beebe et al. (2011) found that "optimal midrange" of synchrony – a midpoint between too little coordination, marking withdrawal, and too high coordination, indicating high vigilance – is most adaptive for infant development and we similarly found that increased behavioral synchrony is characteristic of interactions between clinically-anxious mothers and their infants (Granat et al., 2016). Our findings suggest that this may be the case with regards to physiological synchrony of HPA-axis functioning so that high diurnal CT concordance is associated with less adaptive interactions and increased CT secretion. Indeed, studies have shown that in the context of maladaptive familial patterns, such

Table 4
Two-level models showing mother cortisol as a predictor of child cortisol, with moderators: fixed effects with robust standard errors (n = 97 dyads).

	Model 1			Model 2		
	Mother-child dyadic reciprocity			Mother-child dyadic tension		
	Estimate	SE	t ratio	Estimate	SE	t ratio
Fixed effects						
Cortisol intercept	1528.93	30.59	49.97**	1528.93	30.59	49.97**
Level 2 covariates - mother cortisol						
Intercept	0.32	0.06	5.08**	0.31	0.06	5.21**
Group	−0.03	0.04	−0.79	−0.01	0.04	−0.26
Moderator	−0.12	0.06	−2.05*	0.06	0.08	0.72
Level 2 covariates - time						
Intercept	−324.98	53.38	−6.09**	−324.65	53.34	−6.16**

* $p < 0.05$.
** $p < 0.001$.

as partner violence, punitive parenting (Hibel et al., 2009), low affective sharing (Williams et al., 2013), and maternal psychopathology (LeMoult et al., 2015), high adrenocortical synchrony is an index of high vigilance. This is in contrast to periodic stress and stress that is external to the relational context, where adrenocortical synchrony correlates with behavioral attunement and may index greater adaptation (Atkinson et al., 2013; Hibel et al., 2015; Ruttle et al., 2011; Sethre-Hofstad et al., 2002). Much further research is required to test this hypothesis in children of varying ages, different family contexts, in relation to various physiological and behavioral systems, and following interventions that target intra-familial stress and violence.

Most studies on mother-child CT linkage examined it in relation to manipulated stress and the term "stress-contagion" (Waters et al., 2013) was coined to define this mechanism. Stress contagion refers to the mutual escalation of stress within a relationship, where partners enhance each other's stress rather than help downregulate it (Saxbe and Repetti, 2010; Saxbe et al., 2014). In synchrony of diurnal CT patterns it is difficult to infer stress contagion mechanisms. Based on our model, we speculate that diurnal CT coordination is formed partially through the accumulation of shared experiences of CT synchronization during stressful moments but that adrenocortical synchrony of diurnal patterns may generalize and become independent from the concordance of momentary CT production. Much further research is required to assess the associations between adrenocortical synchrony of diurnal patterns with maternal and child stress experienced during the day, the relations between diurnal and reactivity patterns of CT attunement, and the longitudinal development of diurnal concordance from infancy to childhood.

Chronic maternal depression did not moderate the concordance between maternal and child's diurnal CT. This finding is consistent with previous research in adolescent daughters of depressed mothers (LeMoult et al., 2015), but not with a study of infants exposed to postpartum depression (Laurent et al., 2011). In the latter, when infants were exposed to postpartum depression, but were not exposed to prenatal depression, correlations between maternal and child CT secretion were higher. Such high correlations were not observed when infants were exposed to maternal depression both pre- and post-birth and the authors hypothesized that shifts in maternal mental health increases infant alertness signals from the mother, creating greater coordination in CT production (Laurent et al., 2011). This explanation may also be relevant to understanding the differences between prior research and our study, in which children were exposed to maternal depression from infancy to preschool age with little shifts in mother diagnosis. In combination, findings may suggest that maternal depression per-se is not related to mother-child adrenocortical attunement, but that shifts in maternal depressed mood may lead to greater synchrony. Yet, it is important to note that maternal depression is associated with disrupted child HPA-axis functioning. Major depression has been associated with higher CT levels and blunted CT variability (Burke et al., 2005; Hankin et al., 2010), and children of depressed mothers were repeatedly found to display maladaptive CT patterns, expressed in both diurnal patterns (Halligan et al., 2004; Laurent et al., 2013; LeMoult et al., 2015; Luijk et al., 2010) and in response to acute stress (Essex et al., 2002; Feldman et al., 2009; Murray et al., 2010). Our findings show that children growing up in the context of chronic maternal depression display blunted diurnal CT decline and such HPA-system inflexibility has been found to place children at higher risk (Badanes et al., 2011; Juster et al., 2010; Raison and Miller, 2003).

Our study did not test the role of genetic makeup in supporting adrenocortical synchrony and this is an alternative explanation. While genes certainly contribute to hormonal concordance, it is likely that at least a portion of the shared variance is mediated by environmental experiences. The moderating effect of mother-child reciprocity on the correlation between maternal and child diurnal CT secretion lends support to the hypothesis that the rearing environment played some role in mother-child CT linkage. Twin studies examining familial co-variation in CT found that shared environment was a better predictor of afternoon CT secretion and correlation between CT levels did not differ between monozygotic and dizygotic twins (Schreiber et al., 2006), while morning CT was more impacted by genetic factors (Bartels et al., 2003). Much further research is thus required to examine the interplay of shared genes and shared environment on adrenocortical synchrony.

Several limitations are important to consider in the interpretation of the findings. First, although salivary cortisol is a well-researched method, it is a peripheral measure and may not reflect central nervous system activity. Second, since cortisol and behavioral measurements were collected in the same period of time, it is impossible to infer causality. Both parenting and diurnal patterns evolve over lengthy periods and are associated with a myriad of factors that have not been tested here. Mother and child CT were measured at the same time-points and we can thus only suggest cross-correlation between CT levels. Finally, our findings are preliminary and require much further research to better understand the contexts in which diurnal CT correlations are associated with positive or less optimal relational patterns and to incorporate longitudinal measures collected at various dyadic contexts to further understand the complex nature of adrenocortical synchrony as it evolves within close relationships.

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References

Albers, E.M., Marianne Riksen-Walraven, J., Sweep, F.C.G.J., de Weerth, C., 2008. Maternal behavior predicts infant cortisol recovery from a mild everyday stressor. J. Child Psychol. Psychiatry 49:97–103. http://dx.doi.org/10.1111/j.1469-7610.2007.01818.x.

Apter-Levi, Y., Pratt, M., Vakart, A., Feldman, M., Zagoory-Sharon, O., Feldman, R., 2016. Maternal depression across the first years of life compromises child psychosocial adjustment; relations to child HPA-axis functioning. Psychoneuroendocrinology 64: 47–56. http://dx.doi.org/10.1016/j.psyneuen.2015.11.006.

Atkinson, L., Gonzalez, A., Kashy, D.A., Santo Basile, V., Masellis, M., Pereira, J., Chisholm, V., Levitan, R., 2013. Maternal sensitivity and infant and mother adrenocortical function across challenges. Psychoneuroendocrinology 38:2943–2951. http://dx.doi.org/10.1016/j.psyneuen.2013.08.001.

Badanes, L.S., Watamura, S.E., Hankin, B.L., 2011. Hypocortisolism as a potential marker of allostatic load in children: associations with family risk and internalizing disorders. Dev. Psychopathol. 23:881–896. http://dx.doi.org/10.1017/S095457941100037X.

Barker, E.D., 2013. The duration and timing of maternal depression as a moderator of the relationship between dependent interpersonal stress, contextual risk and early child dysregulation. Psychol. Med. 43:1587–1596. http://dx.doi.org/10.1017/S0033291712002450.

Bartels, M., de Geus, E.J.C., Kirschbaum, C., Sluyter, F., Boomsma, D.I., 2003. Heritability of daytime cortisol levels in children. Behav. Genet. 33, 421–433.

Beck, A.T., Ward, C.H., Mendelson, M., Mock, J., Erbaugh, J., 1961. An inventory for measuring depression. Arch. Gen. Psychiatry 4, 561–571.

Beebe, B., Steele, M., Jaffe, J., Buck, K.A., Chen, H., Cohen, P., Kaitz, M., Markese, S., Andrews, H., Margolis, A., Feldstein, S., 2011. Maternal anxiety symptoms and mother-infant self- and interactive contingency. Infant Ment. Health J. 32:174–206. http://dx.doi.org/10.1002/imhj.20274.

Brennan, P.A., Pargas, R., Walker, E.F., Green, P., Newport, D.J., Stowe, Z., 2008. Maternal depression and infant cortisol: influences of timing, comorbidity and treatment. J. Child Psychol. Psychiatry 49:1099–1107. http://dx.doi.org/10.1111/j.1469-7610.2008.01914.x.

Brummelte, S., Grunau, R.E., Zaidman-Zait, A., Weinberg, J., Nordstokke, D., Cepeda, I.L., 2011. Cortisol levels in relation to maternal interaction and child internalizing behavior in preterm and full-term children at 18 months corrected age. Dev. Psychobiol. 53: 184–195. http://dx.doi.org/10.1002/dev.20511.

Burke, H.M., Davis, M.C., Otte, C., Mohr, D.C., 2005. Depression and cortisol responses to psychological stress: a meta-analysis. Psychoneuroendocrinology 30:846–856. http://dx.doi.org/10.1016/j.psyneuen.2005.02.010.

Cabrera, N.J., Shannon, J.D., Tamis-LeMonda, C., 2007. Fathers' influence on their children's cognitive and emotional development: from toddlers to pre-K. Appl. Dev. Sci. 11: 208–213. http://dx.doi.org/10.1080/10888690701762100.

Champagne, F., Meaney, M.J., 2001. Like mother, like daughter: evidence for non-genomic transmission of parental behavior and stress responsivity. Prog. Brain Res. 133, 287–302.

Davis, E.P., Glynn, L.M., Waffarn, F., Sandman, C.A., 2011. Prenatal maternal stress programs infant stress regulation. J. Child Psychol. Psychiatry Allied Discip. 52: 119–129. http://dx.doi.org/10.1111/j.1469-7610.2010.02314.x.

Edwards, S., Clow, A., Evans, P., Hucklebridge, F., 2001. Exploration of the awakening cortisol response in relation to diurnal cortisol secretory activity. Life Sci. 68:2093–2103. http://dx.doi.org/10.1016/S0024-3205(01)00996-1.

Essex, M.J., Klein, M.H., Miech, R., Smider, N.A., 2001. Timing of initial exposure to maternal major depression and children's mental health symptoms in kindergarten. Br. J. Psychiatry 179:151–156. http://dx.doi.org/10.1192/bjp.179.2.151.

Essex, M.J., Klein, M.H., Cho, E., Kalin, N.H., 2002. Maternal stress beginning in infancy may sensitize children to later stress exposure: effects on cortisol and behavior. Biol. Psychiatry 52, 776–784.

Essex, M.J., Shirtcliff, E.A., Burk, L.R., Ruttle, P.L., Klein, M.H., Slattery, M.J., Kalin, N.H., Armstrong, J.M., 2011. Influence of early life stress on later hypothalamic–pituitary–adrenal axis functioning and its covariation with mental health symptoms: a study of the allostatic process from childhood into adolescence. Dev. Psychopathol. http://dx.doi.org/10.1017/S0954579411000484.

Feldman, R., 2006. From biological rhythms to social rhythms: physiological precursors of mother-infant synchrony. Dev. Psychol. 42:175–188. http://dx.doi.org/10.1037/0012-1649.42.1.175.

Feldman, R., 2007a. Parent–infant synchrony: biological foundations and developmental outcomes. Curr. Dir. Psychol. Sci. 16:340–345. http://dx.doi.org/10.1111/j.1467-8721.2007.00532.x.

Feldman, R., 2007b. Parent-infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. J. Child Psychol. Psychiatry 48:329–354. http://dx.doi.org/10.1111/j.1469-7610.2006.01701.x.

Feldman, R., 2010. The relational basis of adolescent adjustment: trajectories of mother–child interactive behaviors from infancy to adolescence shape adolescents' adaptation. Attach Hum. Dev. 12, 173–192.

Feldman, R., 2012a. Parent – infant synchrony: a biobehavioral model of mutual influences in the formation of affiliative bonds. Monogr. Soc. Res. Child Dev. 42–51.

Feldman, R., 2012b. Bio-behavioral synchrony: a model for integrating biological and microsocial behavioral processes in the study of parenting. Parenting 12:154–164. http://dx.doi.org/10.1080/15295192.2012.683342.

Feldman, R., 2012c. Parenting behavior as the environment where children grow. In: Mayes, L.C., Lewis, M. (Eds.), The Cambridge Handbook of Environment in Human Development. Cambridge University Press, New York, pp. 535–1102.

Feldman, R., 2015a. The adaptive human parental brain: implications for Children's social growth. Trends Neurosci. 38, 387–399.

Feldman, R., 2015b. Sensitive periods in human social development; new insights from research on oxytocin, synchrony, and high-risk parenting. Dev. Psychopathol. 27, 369–395.

Feldman, R., 2016. The neurobiology of mammalian parenting and the biosocial context of human caregiving. Horm. Behav. 77, 3–17.

Feldman, R., Granat, A., Pariente, C., Kanety, H., Kuint, J., Gilboa-Schechtman, E., 2009. Maternal depression and anxiety across the postpartum year and infant social engagement, fear regulation, and stress reactivity. J. Am. Acad. Child Adolesc. Psychiatry 48:919–927. http://dx.doi.org/10.1097/CHI.0b013e3181b21651.

Feldman, R., Gordon, I., Zagoory-Sharon, O., 2010a. The cross-generation transmission of oxytocin in humans. Horm. Behav. 58:669–676. http://dx.doi.org/10.1016/j.yhbeh.2010.06.005.

Feldman, R., Singer, M., Zagoory, O., 2010b. Touch attenuates infants' physiological reactivity to stress. Dev. Sci. 13:271–278. http://dx.doi.org/10.1111/j.1467-7687.2009.00890.x.

Feldman, R., Magori-Cohen, R., Singer, M., Galili, G., Louzoun, Y., 2011. Mother and infant coordinate heart rhythms through episodes of interaction synchrony. Infant Behav. Dev. 34, 569–577.

Feldman, R., Bamberger, E., Kanat-Maymon, Y., 2013a. Parent-specific reciprocity from infancy to adolescence shapes children's social competence and dialogical skills. Attach Hum. Dev. 15, 407–423.

Feldman, R., Vengrober, A., Eidelman-Rothman, M., Zagoory-Sharon, O., 2013b. Stress reactivity in war-exposed young children with and without posttraumatic stress disorder: relations to maternal stress hormones, parenting, and child emotionality and regulation. Dev. Psychopathol. 25:943–955. http://dx.doi.org/10.1017/S0954579413000291.

First, M., Spitzer, R., Gibbon, M., Williams, J., 1997. Structured Clinical Interview for DSM–IV Axis I Disorders-Clinician Version (SCID-CV). American Psychiatric Press, Washington, DC.

Francis, D.D., Meaney, M.J., 1999. Maternal care and the development of stress responses. Curr. Opin. Neurobiol. 9, 128–134.

Gitau, R., Fisk, N.M., Teixeira, J.M., Cameron, A., Glover, V., 2001. Fetal hypothalamic-pituitary-adrenal stress responses to invasive procedures are independent of maternal responses. J. Clin. Endocrinol. Metab. 86:104–109. http://dx.doi.org/10.1210/jcem.86.1.7090.

Granat, A., Gadassi, R., Gilboa-Schechtman, E., Feldman, R., 2016. Maternal depression and anxiety, social synchrony, and infant regulation of negative and positive emotions. Emotion (Jul 21. Epub ahead of print).

Gubernick, D.J., Alberts, J.R., 1983. Maternal licking of young: resource exchange and proximate controls. Physiol. Behav. 31, 593–601.

Gunnar, M.R., Donzella, B., 2002. Social regulation of the cortisol levels in early human development. Psychoneuroendocrinology http://dx.doi.org/10.1016/S0306-4530(01)00045-2.

Gunnar, M., Quevedo, K., 2007. The neurobiology of stress and development. Annu. Rev. Psychol. 58:145–173. http://dx.doi.org/10.1146/annurev.psych.58.110405.085605.

Gunnar, M.R., Vazquez, D.M., 2001. Low cortisol and a flattening of expected daytime rhythm: potential indices of risk in human development. Dev. Psychopathol. 13, 515–538.

Gutteling, B.M., de Weerth, C., Buitelaar, J.K., 2004. Maternal prenatal stress and 4–6 year old children's salivary cortisol concentrations pre- and post-vaccination. Stress 7: 257–260. http://dx.doi.org/10.1080/10253890500044521.

Gutteling, B.M., de Weerth, C., Buitelaar, J.K., 2005. Prenatal stress and children's cortisol reaction to the first day of school. Psychoneuroendocrinology 30:541–549. http://dx.doi.org/10.1016/j.psyneuen.2005.01.002.

Halligan, S.L., Herbert, J., Goodyer, I.M., Murray, L., 2004. Exposure to postnatal depression predicts elevated cortisol in adolescent offspring. Biol. Psychiatry 55:376–381. http://dx.doi.org/10.1016/j.biopsych.2003.09.013.

Hankin, B.L., Badanes, L.S., Abela, J.R.Z., Watamura, S.E., 2010. Hypothalamic-pituitary-adrenal axis dysregulation in dysphoric children and adolescents: cortisol reactivity to psychosocial stress from preschool through middle adolescence. Biol. Psychiatry 68: 484–490. http://dx.doi.org/10.1016/j.biopsych.2010.04.004.

Hart, J., Gunnar, M., Cicchetti, D., 2009. Salivary cortisol in maltreated children: evidence of relations between neuroendocrine activity and social competence. Dev. Psychopathol. 7:11. http://dx.doi.org/10.1017/S0954579400006313.

Hastings, P.D., Ruttle, P.L., Serbin, L.A., Mills, R.S.L., Stack, D.M., Schwartzman, A.E., 2011. Adrenocortical responses to strangers in preschoolers: relations with parenting, temperament, and psychopathology. Dev. Psychobiol. 53:694–710. http://dx.doi.org/10.1002/dev.20545.

Hibel, L.C., Granger, D.A., Blair, C., Cox, M.J., 2009. Intimate partner violence moderates the association between mother–infant adrenocortical activity across an emotional challenge. J. Fam. Psychol. 23:615–625. http://dx.doi.org/10.1037/a0016323.

Hibel, L.C., Trumbell, J.M., Mercado, E., 2014. Work/non-workday differences in mother, child, and mother-child morning cortisol in a sample of working mothers and their children. Early Hum. Dev. 90:1–7. http://dx.doi.org/10.1016/j.earlhumdev.2013.11.007.

Hibel, L.C., Granger, D.A., Blair, C., Finegood, E.D., 2015. Maternal-child adrenocortical attunement in early childhood: continuity and change. Dev. Psychobiol. 57:83–95. http://dx.doi.org/10.1002/dev.21266.

Hofer, M.A., 1995. Hidden regulators. Attach. Theory Soc. Dev. Clin. Perspect. 203–230.

Juster, R.P., McEwen, B.S., Lupien, S.J., 2010. Allostatic load biomarkers of chronic stress and impact on health and cognition. Neurosci. Biobehav. Rev. 35:2–16. http://dx.doi.org/10.1016/j.neubiorev.2009.10.002.

Kochanska, G., Murray, K.T., 2000. Mother - child mutually responsive orientation and conscience development: from toddler to early school age. Child Dev. 71:417–431. http://dx.doi.org/10.1111/1467-8624.00154.

Kundakovic, M., Champagne, F.A., 2015. Early-life experience, epigenetics, and the developing brain. Neuropsychopharmacology 40:141–153. http://dx.doi.org/10.1038/npp.2014.140.

Laurent, H.K., Ablow, J.C., Measelle, J., 2011. Risky shifts: how the timing and course of mothers' depressive symptoms across the perinatal period shape their own and infant's stress response profiles. Dev. Psychopathol. 23:521–538. http://dx.doi.org/10.1017/S0954579411000083.

Laurent, H.K., Leve, L.D., Neiderhiser, J.M., Natsuaki, M.N., Shaw, D.S., Harold, G.T., Reiss, D., 2013. Effects of prenatal and postnatal parent depressive symptoms on adopted child HPA regulation: independent and moderated influences. Dev. Psychol. 49:876–886. http://dx.doi.org/10.1037/a0028800.

LeMoult, J., Chen, M.C., Foland-Ross, L.C., Burley, H.W., Gotlib, I.H., 2015. Concordance of mother-daughter diurnal cortisol production: understanding the intergenerational transmission of risk for depression. Biol. Psychol. 108:98–104. http://dx.doi.org/10.1016/j.biopsycho.2015.03.019.

Liu, D., Diorio, J., Tannenbaum, B., Caldji, C., Francis, D., Freedman, A., Sharma, S., Pearson, D., Plotsky, P.M., Meaney, M.J., 1997. Maternal care, hippocampal glucocorticoid receptors, and hypothalamic-pituitary-adrenal responses to stress. Science 277 (80): 1659–1662. http://dx.doi.org/10.1126/science.277.5332.1659.

Liu, S., Rovine, M.J., Cousino Klein, L., Almeida, D.M., 2013. Synchrony of diurnal cortisol pattern in couples. J. Fam. Psychol. 27:579–588. http://dx.doi.org/10.1037/a0033735.

Luijk, M.P.C.M., Saridjan, N., Tharner, A., Van Ijzendoorn, M.H., Bakermans-Kranenburg, M.J., Jaddoe, V.W.V., Hofman, A., Verhulst, F.C., Tiemeier, H., 2010. Attachment, depression, and cortisol: deviant patterns in insecure-resistant and disorganized infants. Dev. Psychobiol. 52:441–452. http://dx.doi.org/10.1002/dev.20446.

MacLean, P.C., Rynes, K.N., Aragón, C., Caprihan, A., Phillips, J.P., Lowe, J.R., 2014. Mother-infant mutual eye gaze supports emotion regulation in infancy during the still-face paradigm. Infant Behav. Dev. 37:512–522. http://dx.doi.org/10.1016/j.infbeh.2014.06.008.

Macrì, S., Zoratto, F., Laviola, G., 2011. Early-stress regulates resilience, vulnerability and experimental validity in laboratory rodents through mother-offspring hormonal transfer. Neurosci. Biobehav. Rev. 35:1534–1543. http://dx.doi.org/10.1016/j.neubiorev.2010.12.014.

McEwen, B.S., 1998. Stress, adaptation, and disease: allostasis and allostatic load. Ann. N. Y. Acad. Sci. 840:33–44. http://dx.doi.org/10.1111/j.1749-6632.1998.tb09546.x.

Mogi, K., Nagasawa, M., Kikusui, T., 2011. Developmental consequences and biological significance of mother – infant bonding. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 35:1232–1241. http://dx.doi.org/10.1016/j.pnpbp.2010.08.024.

Moore, G.A., Calkins, S.D., 2004. Infants' vagal regulation in the still-face paradigm is related to dyadic coordination of mother-infant interaction. Dev. Psychol. 40:1068–1080. http://dx.doi.org/10.1037/0012-1649.40.6.1068.

Mörelius, E., Theodorsson, E., Nelson, N., 2009. Stress at three-month immunization: parents' and infants' salivary cortisol response in relation to the use of pacifier and oral glucose. Eur. J. Pain 13.

Mörelius, E., Broström, E.B., Westrup, B., Sarman, I., Örtenstrand, A., 2012. The Stockholm Neonatal Family-centered Care Study: effects on salivary cortisol in infants and their mothers. Early Hum. Dev. 88:575–581. http://dx.doi.org/10.1016/j.earlhumdev.2011.12.033.

Mörelius, E., Örtenstrand, A., Theodorsson, E., Frostell, A., 2015. A randomised trial of continuous skin-to-skin contact after preterm birth and the effects on salivary cortisol, parental stress, depression, and breastfeeding. Early Hum. Dev. 91:63–70. http://dx.doi.org/10.1016/j.earlhumdev.2014.12.005.

Murray, L., Halligan, S.L., Goodyer, I., Herbert, J., 2010. Disturbances in early parenting of depressed mothers and cortisol secretion in offspring: a preliminary study. J. Affect. Disord. 122:218–223. http://dx.doi.org/10.1016/j.jad.2009.06.034.

Neu, M., Laudenslager, M., Robinson, J., 2009. Coregulation in salivary cortisol during maternal holding of premature infants. Biol. Res. Nurs. 10, 226–240.
O'Donnell, K.J., Glover, V., Jenkins, J., Browne, D., Ben-Shlomo, Y., Golding, J., O'Connor, T.G., 2013. Prenatal maternal mood is associated with altered diurnal cortisol in adolescence. Psychoneuroendocrinology 38:1630–1638. http://dx.doi.org/10.1016/j.psyneuen.2013.01.008.
Papp, L.M., Pendry, P., Adam, E.K., 2009. Mother-adolescent physiological synchrony in naturalistic settings: within-family cortisol associations and moderators. J. Fam. Psychol. 23:882–894. http://dx.doi.org/10.1037/a0017147.
Pratt, M., Singer, M., Kanat-Maymon, Y., Feldman, R., 2015. Infant negative reactivity defines the effects of parent–child synchrony on physiological and behavioral regulation of social stress. Dev. Psychopathol. 27:1191–1204. http://dx.doi.org/10.1017/S0954579415000760.
Pruessner, J.C., Kirschbaum, C., Meinlschmid, G., Hellhammer, D.H., 2003. Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. Psychoneuroendocrinology 28:916–931. http://dx.doi.org/10.1016/S0306-4530(02)00108-7.
Raison, C.L., Miller, A.H., 2003. When not enough is too much: the role of insufficient glucocorticoid signaling in the pathophysiology of stress-related disorders. Am. J. Psychiatry 160:1554–1565. http://dx.doi.org/10.1176/appi.ajp.160.9.1554.
Raudenbush, A., Bryk, A., Cheong, Y.F., Congdon, R., Du Toit, M., 2011. Hierarchical Linear and Nonlinear Modeling (HLM7). Scientific Software International Inc., Lincolnwood, IL.
Rosenberg, K.M., Denenberg, V.H., Zarrow, M.X., 1970. Mice (*Mus musculus*) reared with rat aunts: the role of rat-mouse contact in mediating behavioural and physiological changes in the mouse. Anim. Behav. 18, 138–143.
Ruttle, P.L., Serbin, L.A., Stack, D.M., Schwartzman, A.E., Shirtcliff, E.A., 2011. Adrenocortical attunement in mother – child dyads: importance of situational and behavioral characteristics. Biol. Psychol. 88:104–111. http://dx.doi.org/10.1016/j.biopsycho.2011.06.014.
Sandman, C.a., Davis, E.P., Buss, C., Glynn, L.M., 2012. Exposure to prenatal psychobiological stress exerts programming influences on the mother and her fetus. Neuroendocrinology 95:8–21. http://dx.doi.org/10.1159/000327017.
Saxbe, D., Repetti, R.L., 2010. For better or worse? Coregulation of couples' cortisol levels and mood states. J. Pers. Soc. Psychol. 98:92–103. http://dx.doi.org/10.1037/a0016959.
Saxbe, D.E., Margolin, G., Spies Shapiro, L., Ramos, M., Rodriguez, A., Iturralde, E., 2014. Relative influences: patterns of HPA axis concordance during triadic family interaction. Health Psychol. 33:273–281. http://dx.doi.org/10.1037/a0033509.
Schreiber, J., Shirtcliff, E., Hulle, C., Lemerychalfant, K., Klein, M., Kalin, N., Essex, M., Goldsmith, H., 2006. Environmental influences on family similarity in afternoon cortisol levels: twin and parent–offspring designs. Psychoneuroendocrinology 31:1131–1137. http://dx.doi.org/10.1016/j.psyneuen.2006.07.005.
Sethre-Hofstad, L., Stansbury, K., Rice, M.A., 2002. Attunement of maternal and child adrenocortical response to child challenge. Psychone 27, 731–747.
Shirtcliff, E.A., Allison, A.L., Armstrong, J.M., Slattery, M.J., Kalin, N.H., Essex, M.J., 2012. Longitudinal stability and developmental properties of salivary cortisol levels and circadian rhythms from childhood to adolescence. Dev. Psychobiol. 54:493–502. http://dx.doi.org/10.1002/dev.20607.
Spielberger, C.D., Gorsuch, R.L., Lushene, R.E., 1970. State-trait Anxiety Inventory. Consulting Psychologists Press, Palo Alto. Cal.
Stenius, F., Theorell, T., Lilja, G., Scheynius, A., Alm, J., Lindblad, F., 2008. Comparisons between salivary cortisol levels in six-months-olds and their parents. Psychoneuroendocrinology 33:352–359. http://dx.doi.org/10.1016/j.psyneuen.2007.12.001.
Stern, D., 1977. The First Relationship: Infant and Mother. Harvard University Press, Cambridge, MA.
Stright, A.D., Gallagher, K.C., Kelley, K., 2008. Infant temperament moderates relations between maternal parenting in early childhood and children's adjustment in first grade. Child Dev. 79:186–200. http://dx.doi.org/10.1111/j.1467-8624.2007.01119.x.
Tu, M.T., Grunau, R.E., Petrie-Thomas, J., Haley, D.W., Weinberg, J., Whitfield, M.F., 2007. Maternal stress and behavior modulate relationships between neonatal stress, attention, and basal cortisol at 8 months in preterm infants. Dev. Psychobiol. 49:150–164. http://dx.doi.org/10.1002/dev.20204.
Velders, F.P., Dieleman, G., Cents, R.A.M., Bakermans-Kranenburg, M.J., Jaddoe, V.W.V., Hofman, A., Van Ijzendoorn, M.H., Verhulst, F.C., Tiemeier, H., 2012. Variation in the glucocorticoid receptor gene at rs41423247 moderates the effect of prenatal maternal psychological symptoms on child cortisol reactivity and behavior. Neuropsychopharmacology 37:2541–2549. http://dx.doi.org/10.1038/npp.2012.118.
Waters, C.S., Goozen, S., Phillips, R., Swift, N., Hurst, S.L., Mundy, L., Jones, R., Jones, I., Goodyer, I., Hay, D.F., 2013. Infants at familial risk for depression show a distinct pattern of cortisol response to experimental challenge. J. Affect. Disord. 150:955–960. http://dx.doi.org/10.1016/j.jad.2013.04.054.
Waters, S.F., West, T.V., Mendes, W.B., 2014. Stress contagion: physiological covariation between mothers and infants. Psychol. Sci. 25:934–942. http://dx.doi.org/10.1177/0956797613518352.
Williams, S.R., Cash, E., Daup, M., Geronimi, E.M.C., Sephton, S.E., Woodruff-Borden, J., 2013. Exploring patterns in cortisol synchrony among anxious and nonanxious mother and child dyads: a preliminary study. Biol. Psychol. 93:287–295. http://dx.doi.org/10.1016/j.biopsycho.2013.02.015.
Zijlmans, M.A.C., Riksen-walraven, J.M., Weerth, C. De, 2015. Associations between maternal prenatal cortisol concentrations and child outcomes: a systematic review. Neurosci. Biobehav. Rev. 53:1–24. http://dx.doi.org/10.1016/j.neubiorev.2015.02.015.