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Mother-Adolescent Physiological Synchrony in Naturalistic Settings: Within-Family Cortisol Associations and Moderators

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Abstract

In this study, the authors examined parent-adolescent cortisol associations in 45 families with adolescent children (24 girls; M age = 15.78 years, SD = 1.44 years). Family members' salivary cortisol levels were measured 7 times a day on 2 typical weekdays. Family members provided reports of demographic and health variables, and adolescents rated parent-child relationship characteristics. After accounting for the effects of time of day and relevant demographic and health control variables on cortisol levels, hierarchical linear models indicated the presence of significant covariation over time in mother-adolescent cortisol (i.e., physiological synchrony). Furthermore, moderating tests revealed that mother-adolescent cortisol synchrony was strengthened among dyads characterized by mothers and adolescents spending more time together, and in families rated higher on levels of parent-youth shared activities and parental monitoring/supervision. Analysis of momentary characteristics indicated that maternal presence at the time of cortisol sampling lowered adolescent cortisol levels but did not account for mother-adolescent cortisol synchrony. Within-family physiological synchrony was amplified in momentary contexts of elevated maternal negative affect and elevated adolescent negative affect.

Keywords

cortisol; hierarchical linear modeling; parent-child relationships

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Mother-Adolescent Physiological Synchrony in Naturalistic Settings: Within-Family Cortisol Associations and Moderators

Given the emergent recognition of biosocial perspectives by family theorists (Booth, Carver, & Granger, 2000; Cicchetti, 2002; Repetti, Taylor, & Seeman, 2002), studies of family functioning have increasingly incorporated physiological data (e.g., Davies, Sturge-Apple, Cicchetti, & Cummings, 2007; El-Sheikh, 2005; Liew et al., 2003; Pendry & Adam, 2007). Moreover, the joint examination of emotional, physiological, and social systems aligns with a developmental psychopathology framework, thereby facilitating examination of typical and problematic developmental processes of family members (Cummings, Davies, & Campbell, 2000). These biosocial models further postulate ongoing interactions among multiple contexts of family members' development, such that examining the interplay between characteristics of individual functioning (e.g., gender, physical maturity), social environments (e.g., parent-child relations), and physiological functioning is encouraged (Belsky, Bakermans-Kranenburg, & van Ijzendoorn, 2007; Granger & Kivlighan, 2003). Despite this increasing consideration of physiological processes by family psychology researchers, questions remain about the interconnections among such processes at a *within-family* level. Following a family systems perspective (Cox & Paley, 2003), indicators of family members' physiological processes are expected to inter-relate over time, yet systematic investigations of such associations are lacking. Using a naturalistic approach, this investigation models within-family associations of parents' and adolescents' cortisol levels, markers of a physiological system thought to have particular relevance for family functioning. In accord with previous documentations of consistent maternal effects on youth responding and outcomes (e.g., Feldman, 2007; Hooven, Gottman, & Katz, 1995), the present study focuses on testing associations between mothers' and adolescents cortisol levels as an initial explication of within-family physiological functioning.

Cortisol and Family Functioning

The hormone cortisol is the main product of the hypothalamic-pituitary-adrenal (HPA) axis, one of the body's primary physiological stress-response systems. Among numerous indicators of physiologic responding, examination of patterns of family members' *cortisol* production holds particular promise for the field of family psychology on the basis of its connection to social, emotional, and psychological events (Adam, 2005). Typically, healthy adolescents and adults show a pronounced diurnal pattern of cortisol, in which levels are highest in the morning soon after waking, drop rapidly in the first few hours after waking, and then continue to drop more slowly, reaching a low point around midnight (Clow, Thorn, Evans, & Hucklebridge, 2004; Lovallo, 2006). Indeed, time of day has been shown to account for approximately 70% of the variation in cortisol levels (Adam & Gunnar, 2001). Beyond basal patterns of cortisol production attributable to the time of day, cortisol functioning is also determined by momentary environmental influences, such as responding to social stressors (e.g., family conflict; Davies et al., 2007). Importantly, cortisol is also affected by a range of health variables, including nicotine use (Lovallo, 2006) and oral contraceptives (Schreiber et al., 2006), which must be accounted for in substantive analyses.

Mother-Adolescent Physiological Synchrony

Despite the lack of knowledge about the interplay between family members' physiological processes, examples of biological synchrony between mother and child during early developmental stages have been found (i.e., accordance between social gaze, arousal levels, and vocalizing; Feldman, 2007). Further, numerous investigations have yielded associations between emotions reported by family members (i.e., "contagion;" Larson & Almeida, 1999), with maternal positivity and anger predicting increases in the respective feelings as experienced

by teenagers (Matjasko & Feldman, 2005). Given that families are important in terms of regulating children's biological development and affective experiences, we also expect them to contribute to youths' ongoing physiologic responding. We propose that such accordance could be seen by examining covariation among cortisol levels sampled contemporaneously from multiple family members across the day, after having accounted for typical diurnal changes in cortisol. To the extent that analyses are able to statistically account for other factors related to cortisol and HPA activity, including time of day and demographic and health control variables, within-family physiological synchrony, or reliable covariation between family members' cortisol processes, would be established.

Family Characteristics and Youth Cortisol

Underscoring the wide-spread role of family processes in physiological functioning, studies conducted to date suggest that both positive and negative family characteristics are associated with youths' HPA levels and activity. As an example, Chryssanthopoulou, Turner-Cobb, Lucas, and Jessop (2005) reported that children aged 3-4.5 years from either highly emotional expressive or highly reserved families had elevated cortisol levels (i.e., cortisol sampled in the evening and throughout the day) relative to children from moderately expressive families. Recently, Blair and colleagues (2008) collected young children's cortisol in response to emotionally-arousing tasks, and found observed parenting in infancy (i.e., maternal engagement at 7 months) was positively associated with concurrent cortisol reactivity and negatively associated with overall cortisol levels in toddlerhood (at 15 months), which suggests the effect of early parenting on development of efficient stress responses. Results from another study indicated that young children of mothers experiencing high levels of stress during a current pregnancy via elevated daily hassles and problems had increased cortisol compared to children of pregnant mothers with lower stress levels (Gutteling, de Weerth, & Buitelaar, 2005), providing further support of linkages between parental processes and youth cortisol.

Research has demonstrated that the quality of relationships between family members also predicts children's physiological adjustment. In line with a "risky families" perspective on child outcomes (Repetti et al., 2002), Pendry and Adam (2007) tested the effects of problematic marital functioning and unsupportive parenting on children's basal HPA axis activity. Their results documented linkages between children's basal cortisol levels and marital functioning, such that elevated marital functioning (e.g., greater use of conflict resolution tactics, higher marital satisfaction) was associated with lower average cortisol levels across the day for kindergartners and adolescents. They also found that lower marital functioning in the home was associated with significantly higher cortisol levels in the evening for younger children as compared to older children, contributing to their flatter diurnal slopes, which are considered less adaptive patterns of cortisol rhythms (Pendry & Adam, 2007). Seeking to understand the role of child cortisol in how marital conflict predicts child maladjustment, Davies and colleagues (2007) measured cortisol reactivity to a simulated marital conflict situation in a sample of kindergarten children. This cortisol reactivity emerged as a significant intervening mechanism in the connection between global interparental conflict and child externalizing symptoms, but not internalizing symptoms, over time (Davies et al., 2007). Recent work has also implicated parent-child relationships in child physiological functioning. In particular, Smeeckens, Riksen-Walraven, and van Bakel (2007) examined 5-year-olds' salivary cortisol levels before and after an observed parent-child task designed to elicit emotionality (i.e., discussion of past emotional events). More negative parent-child interactions (e.g., parental hostility, child negativity), but not positive interactions (e.g., effective parental guidance), observed during the task were related to significantly stronger cortisol reactivity. In sum, the family context has clear implications for youth cortisol, although questions remain concerning inter-relations between family members' physiological processes.

Evidence provided by the study of emotional transmissions within families suggests that such transmissions are not necessarily consistent across all dyads or families (Larson & Richards, 1994). Specifically, variations in mother-adolescent emotions associations would be expected depending on child characteristics (i.e., gender; Larson & Richards, 1994; pubertal development; Kiess et al., 1995) and family characteristics (e.g., parent-child closeness; Larson & Gillman, 1999). Although parent-youth physiological processes are less commonly studied, there is reason to expect that not all families would be equally synchronous. Thus, testing family and child characteristics as potential moderators of any examined within-family physiological processes is essential.

Although most research has focused on associations between basal cortisol activity and trait-like individual and family characteristics, there is also some evidence to suggest that momentary, within-person changes in mood and social environment have implications for changes in cortisol in adults and adolescents as they go about their daily lives. In separate analyses of adolescents and their parents from the same data set as the present study, Adam (2005, 2006) found that cortisol levels were higher at moments when individuals were experiencing negative emotion, and (for parents only) lower when they were experiencing positive-social emotions. This work also indicated that who individuals were with or not with at the time of the sample predicted variations in cortisol levels at that time: Cortisol levels were significantly higher at moments when younger adolescents reported being alone compared to when they were with friends or family members, but this effect was not found for older adolescents or adults. All of this prior work, however, examines how individuals' own moods and experiences relate to their own cortisol levels, rather than examining how family members' physiological processes are interrelated across the day, or how the affective experiences of one family member might affect the physiology of another. The present study extends earlier work by considering how mothers' cortisol levels and affective states, along with adolescent affect, are related to adolescent cortisol across the day.

The Present Study and Hypotheses

Building upon established inter-connections between family members, and recent evidence that family functioning is important to youth cortisol, the present study examined physiological synchrony between maternal cortisol and adolescent cortisol in naturalistic settings. Several studies indicate the presence of normative developmental increases in cortisol levels over the pubertal and postpubertal period (Adam, 2006; Kiess et al., 1995; Lupien, King, Meaney, & McEwen, 2001). For example, adolescents who reported more advanced pubertal development showed daytime basal cortisol curves that were more elevated, had a steeper diurnal decline, and showed a less pronounced cortisol awakening response (Adam, 2006). Other studies have documented gender differences in cortisol levels (e.g., Rosmalen et al., 2005). Sampling cortisol across the day for multiple days in family members' natural environments enabled us to reliably model and account for cortisol daily rhythms and to test individual and contextual moderators of within-family physiological covariation (Adam & Gunnar, 2001; Hauner et al., 2008). Using this approach, the present study addressed the following questions:

First, after accounting for other relevant factors, do mothers' and adolescents' cortisol levels demonstrate reliable linkages? Relations among family members' cortisol would be expected due to both genetic and environmental overlap (Schreiber et al., 2006). However, the presence of a significant linkage between *within-person change (covariation over time)* in mother and child cortisol over the course of sampling days, rather than correlations between mother and adolescent basal cortisol, is less likely to be attributable to genetics alone. We predicted that covariation between mother cortisol and adolescent cortisol would be present over the course of the sampling days, given the consistent importance of maternal factors in extant family literature. We expected such associations to be present even after accounting for covariation

due to cortisol's typical diurnal rhythm and other demographic and health factors known to influence cortisol.

Second, do characteristics of families and adolescents moderate mother-child physiologic synchrony? Family characteristics such as the quality of close relationships not only play a major role in adolescent adjustment (Barber, 1997), but also have been shown to explain children's stress hormone activity (Flinn & England, 1995). In the present study, we hypothesized that characteristics indicative of physical and emotional closeness and awareness of children's lives (e.g., time spent together, engaging in activities together, parental monitoring and supervision) would serve to strengthen family members' physiological synchrony. In terms of youth characteristics as moderators, Adam (2006) reported pubertal stage to be a better predictor than adolescent age of important cortisol parameters. Thus, we expected puberty might moderate mother-child physiological synchrony, but given that within-family physiological processes are less understood, this test remains exploratory. We also tested adolescent gender given that it has moderated some parent-youth associations in past research in family contexts (Cota-Robles & Gamble, 2006; Sturge-Apple, Davies, Boker, & Cummings, 2004), although often inconsistently. We further predicted that the effect of parent-child relationship characteristics might depend on youths' pubertal development or gender, and, therefore, we tested adolescent characteristics by parent-child relationship characteristics as moderators of within-family cortisol associations.

Third, if mother and adolescent cortisol levels sampled across the day are positively associated with each other, do momentary characteristics of being together or family members' affect serve as underpinnings of the synchrony? We expected that being in the presence of the parent during reporting and the affective characteristics of the situation, including both mother and adolescent affective states, would help to account for the degree of synchrony observed between mother and adolescent cortisol levels. Given the important connections between negative emotions in particular as influences on basal cortisol activity and reactivity (Adam, 2006; Adam, Hawkey, Kudielka, & Cacioppo, 2006), we hypothesized that family members' higher levels of negative moods would amplify within-family cortisol synchrony.

Method

Participants

Participants were 45 families with adolescent children from primarily two-parent, middle-income families. The data for this study were collected as a follow-up to the Sloan Family Study, conducted by the Alfred P. Sloan Center on Parents, Children and Work at the University of Chicago (B. Schneider & L. Waite, Co-PIs). Parents of children who had participated in the Sloan Family Study were contacted and asked if they would like to be part of an additional "Physical Stress Study," in which we would examine how the stresses of work and family life affected their "physical stress and health." Consistent with our aim of examining within-family cortisol associations and potentially modifying characteristics, we used data provided by families in which cortisol samples were obtained from a teenager and at least one parent, resulting in 45 mother-teen dyads and 23 father-teen dyads (described in Footnote ¹). Participating mothers had a mean age of 46.18 years ($SD = 5.34$ years) and adolescents (24 girls and 21 boys) had a mean age of 15.78 years ($SD = 1.44$ years, range = 13 – 18). Most

¹A variant of this model was tested such that mother cortisol and father cortisol (available for $n = 23$ father-adolescent dyads) were entered as simultaneous predictors of adolescent cortisol. Results indicated that mother cortisol ($\gamma_{100} = .210, t = 2.33, p < .05$) but not father cortisol ($\gamma_{200} = .071, t = 1.00, p > .05$) was significantly associated with adolescent cortisol. Nevertheless, hypothesis tests conducted in HLM revealed that the strength of the mother-adolescent and father-adolescent cortisol associations did not significantly differ from each other, $\chi^2 (df = 1) = 1.43, p > .05$, suggesting that the present sample's low power to detect effects might preclude detection of father-adolescent physiological synchrony.

adolescents (86.7%) were European American, 4.4% were African American, and the remaining 8.9% were of mixed racial/ethnic background. Most adolescents (75.6%) lived with two parents who were married or in marriage-like, committed relationships, while 17.7% lived with separated or divorced mothers, and 6.5% lived with single mothers.

Procedures

Participants completed a set of diary entries paired with the collection of salivary cortisol samples. Parents and adolescents were asked to complete 7 diary-sample pairs across day from morning to evening for 2 days during the course of their everyday lives. Diary-sample pairs were requested in the morning immediately after waking and 30 minutes after waking, in the evening immediately before bedtime, and 4 times during the day when signaled by a specially programmed watch. The watches were programmed identically for each family member and signals were semi-random, that is they occurred at randomly selected moments within intervals evenly spaced across the day, while avoiding sampling immediately after typical mealtimes. Using the experience sampling method (ESM; Csikszentmihalyi & Larson, 1987), the diary entries involved answering a set of questions about the current situation at the time the watch beeped, including reporting who they were with and their current emotions at the time. A second beep occurred 20 minutes after each beeped diary entry to prompt collection of a related cortisol sample – this protocol was designed to capture cortisol responses to momentary stressors, as it takes 20 to 30 minutes after a stressor for cortisol levels to reach their peak in saliva (Kirschbaum & Hellhammer, 1989).

Cortisol Sampling and Assay Procedures—Each family received a sampling kit including the saliva sampling materials, along with written and pictorial instructions. We also instructed parents and adolescents thoroughly by telephone on how to collect, record, store, and ship saliva samples. Although electronic monitoring of compliance with sample timing was not available in the current study, substantial efforts were made to impress upon participants the importance of compliance with the study's procedures, particularly with regards to the timing of saliva sampling immediately upon waking (Kudielka, Broderick, & Kirschbaum, 2003). These efforts included having participants take a practice sample at least one day before the study began, explaining *why* exact timing of the samples was essential to our study, asking participants to note any sampling issues that had occurred, and suggesting that participants conduct a third day of sampling if saliva sampling of the wakeup sample had been delayed for any reason. We also conducted reminder calls with each participant the evening before they were scheduled to begin saliva collection, at which time sampling procedures were reviewed and suggestions were given to help ensure compliance.

Parents and teens were provided with one piece of Trident® gum and were instructed to chew until it was soft and pliable to help stimulate saliva flow. Participants then expelled saliva through a small straw into a sterile vial and recorded the exact time each sample was taken. Parents and adolescents were instructed to refrigerate samples as soon as possible after they were taken. Given that experimental research has shown that salivary cortisol levels are not affected by variations in temperature and motion similar to those experienced during a trip through the mail system (Clements & Parker, 1998), parents were asked to return the samples to our university-based laboratory by mail. When samples reached our laboratory they were then frozen at –20 degrees Celsius until all data for the study had been collected. Samples were then sent to Salimetrics LLC® laboratory on dry ice, where they were assayed by enzyme immunoassay. The test used for this study (Salimetrics LLC®, High Sensitivity Radioimmune Assay) has a range of sensitivity from .007 to 1.8 µg/dl, and average intra- and inter-assay coefficients of variation less than 3% and 7%, respectively. Consistent with conventions in the literature (Adam, 2006), a normalizing natural logarithmic transformation (base e) was performed on the positively-skewed cortisol data before analyses.

During the completion of the ESM diary-cortisol sample pairs, participants completed a set of surveys reporting on various aspects of family functioning, including parent-child relationship functioning. Each participant also reported on a variety of health and medical issues that might affect cortisol levels. Participants were excluded from analyses if they had a serious chronic health condition that is known to affect endocrine function or used corticosteroid medications. In preliminary analyses, we tested associations between adolescents' average awakening cortisol levels and cortisol slopes (i.e., change across the day) and demographic and health characteristics (i.e., use of caffeine, nicotine, oral contraceptives, gender, BMI, menstrual timing, and pubertal development). Caffeine, gender, BMI, and menstrual timing were not associated with adolescent average awakening cortisol levels or cortisol slopes (all $ps > .10$). Characteristics that were significantly associated with either average awakening cortisol levels or cortisol slopes (i.e., nicotine, oral contraceptives, and pubertal development) were retained as covariates consistently across average levels and slopes in the final models shown below. Adolescent age was included as a control variable to account for potential maturation occurring between the participants' age range of 13 and 18 years.

Measures

Family Characteristics

Time spent together: The ESM diaries contained a question about who participants were with at the time of the beep. We summed the number of instances that the adolescent was in the presence of their mother at the time of the diary beep and then divided this number by the number of diary entries obtained to create a variable that indicated the proportion of time during the diary reporting and related cortisol response period the youth was with their mother over the two days of diary reporting and cortisol sampling ($M = 0.15$, $SD = 0.14$).

Adolescent-parent shared activities: We measured adolescents' engagement in activities with their parents by averaging scores on an activities checklist designed for the purpose of the Sloan Family Study. Specifically, adolescents rated how often they engaged in 15 different activities with one or both parents on a scale of 1 (*rarely or never*) to 4 (*everyday or almost everyday*), including "eating meals together" and "talking about everyday events in our lives" ($M = 2.13$, $SD = 0.41$; $\alpha = .82$).

Parental monitoring and supervision: We measured adolescents' ratings of their parents' monitoring and supervision behaviors by averaging scores of 8 items on a behavioral checklist designed for the purpose of the Sloan Family Study. Adolescents indicated how often on a scale of 0 (*never*) to 3 (*often*) their parents engaged in various parenting behaviors, such as "check on whether you have done your homework" and "ask you to call home when you are out with friends." Adolescents reported an average monitoring and supervision score of 1.70 ($SD = 0.60$; $\alpha = .73$).

Perceived level of attachment to mother: We assessed youths' ratings of perceived attachment to mother by averaging scores on a revised 16-item version of the Inventory of Parent and Peer Attachment (IPPA; Armsden & Greenberg, 1987) used in the Sloan Family Study. Adolescents reported on a scale of 1 (*never true*) to 5 (*always true*) the extent to which they endorse statements such as "my mother accepts me as I am" and "I depend on my mother for help with my problems." The IPPA attempts to measure parental attachment by assessing the "affectively toned cognitive expectancies" (Armsden & Greenberg, 1987, p. 431) associated with internalized representations of attachment to mother. Empirical research on the psychometric properties of the scale showed high internal consistencies (e.g., Armsden & Greenberg, 1987; Paterson, Pryor, & Field, 1995). Furthermore, a high 3-week test-retest reliability has been reported, and the scale appears to possess convergent validity (Armsden & Greenberg, 1987). Adolescents reported an average rating of perceived attachment to mother

of 3.53 ($SD = 0.54$; $\alpha = .85$). See Table 1 for intercorrelations between the present study's adolescent and family characteristics.

Momentary Characteristics—As noted above, the ESM diaries contained a variety of questions, including questions about who participants were with at the time of the beep and their current emotions or affective states at the time of the beep. The question on who participants were with at the time of the beep (used above to create the family-level variable of proportion of time adolescent spent with mother) was also retained as a momentary variable of mother presence coded 0 (*not in presence of mother*) or 1 (*in presence of mother*).

Momentary affective states included were rated on 4-point scales ranging from 0 (*not at all*) to 4 (*very much*). In order to reduce the number of variables used in data analyses and reduce the possibility of Type 1 error, principal component analyses (with a varimax rotation) were performed revealing 2 affect components, including negative affect (frustrated, competitive, stressed, worried, strained, irritated, nervous, lonely, angry) and positive affect (happy, cheerful, cooperative, proud, relaxed, responsible, friendly, caring). Mothers' and adolescents' respective averages for negative affect were 0.43 ($SD = 0.48$) and 0.51 ($SD = 0.56$) and for positive affect were 1.50 ($SD = 0.59$) and 1.22 ($SD = 0.61$). Positive and negative affect were correlated in the expected directions and demonstrated good reliability ($\alpha_{neg} = .95$, $\alpha_{pos} = .83$).

Adolescent Pubertal Development and Health—Adolescents reported pubertal development (Pubertal Development Scale; Peterson, Crockett, Richards, & Boxer, 1988) by evaluating the degree to which a specific physical change such as pimply skin, growth spurt, breast development, or facial hair has occurred. A composite score of the items relevant to each gender was used as their overall measure of pubertal development ($M = 3.32$, $SD = 0.55$). A dummy variable (0 = *no*, 1 = *yes*) was constructed to indicate whether the adolescent reported using an oral contraceptive (endorsed by 6.7% of the sample). Adolescents who used nicotine reported how many cigarettes they typically used per day ($M = 1.11$, $SD = 6.01$; 8.9% of the sample reported using nicotine). Each of these characteristics is suspected to have an influence on cortisol levels (Lovallo, 2006; Netherton, Goodyer, Tamplin, & Herbert, 2004; Schreiber et al., 2006), thereby warranting consideration as a control variable in order for the associations of substantive interest to be properly revealed.

Results

Cortisol Sampling Completion and Descriptive Statistics

Over the course of the two-day reporting period with 14 possible cortisol samples, adolescents provided an average of 10.71 ($SD = 2.93$) cortisol samples and mothers provided an average of 11.98 ($SD = 2.70$) samples. Table 2 shows the descriptive statistics of untransformed cortisol levels collected by family members by sampling occasion averaged across the two reporting days. Examination of mean levels across the course of the day indicates that our cortisol sampling procedures captured the previously documented diurnal rhythm of cortisol (Clow et al., 2004; Kirschbaum & Hellhammer, 1989). Table 2 also presents correlations between mother and adolescent cortisol samples. Examination of these correlations indicates that mother-adolescent cortisol associations at each sampling point ranged from $-.07$ (sample 6) to $.46$ (sample 2) ($r_M = .24$).

Hierarchical Linear Modeling of Mother-Adolescent Physiological Synchrony

We tested our hypotheses using hierarchical level modeling (HLM; Raudenbush & Bryk, 2002). As reviewed by Adam (2005) and Hruschka, Kohrt, and Worthman (2005), modeling repeated assessments of cortisol using HLM offers advantages that include capturing increased statistical power due to the within-person, repeated-measures design, while adjusting for

within-person and within-day nesting of cortisol data and the associated correlated error. In addition, having missing cortisol data points is permissible as long as the individuals provide enough data to model the shape of cortisol across the day. That is, participants are included in analyses even if they do not provide all 7 cortisol samples in one day, although, importantly, greater statistical weight is given to those who provide more reliable estimates. Further, HLM allows simultaneous modeling of the effects of both time-varying (e.g., mother cortisol) and non-time-varying covariates (e.g., health controls) on youths' cortisol levels.

An unconditional hierarchical linear model that regressed on adolescent cortisol the predictors of mother cortisol, time of day, time of day squared, and a dummy variable to indicate a cortisol awakening response (i.e., 30 min after waking) revealed a positive association between mother cortisol and adolescent cortisol (i.e., physiological synchrony), $\gamma_{100} = 0.209$, $t = 3.50$, $p < .001$. As described above, we needed to test for physiological synchrony in a model that included relevant control variables that might account for adolescent cortisol patterns. At Level 1, an adolescent's cortisol values (Y) were predicted by a dummy variable to indicate a cortisol awakening response (CAR; 0 = *not a CAR sample*, 1 = *CAR sample*), time of day (indicated by number of hours since adolescent awakening), and time of day squared (in order to model the non-linear effects of time of day). The remaining variance in adolescents' cortisol across the day, after controlling for diurnal changes and the CAR, was predicted by their mother's cortisol values (matched by sample number 1-7), such that the resulting Level 1 model was:

$$\text{Adolescent Cortisol}_{ij} = \pi_{0ij} + \pi_{1ij}(\text{Mother Cortisol})_{ij} + \pi_{2ij}(\text{CAR})_{ij} + \pi_{3ij}(\text{Time})_{ij} + \pi_{4ij}(\text{Time}^2)_{ij} + e_{ij}$$

At Level 2, we modeled within-day dependency:

$$\begin{aligned}\pi_{0ij} &= \beta_{00j} \\ \pi_{1ij} &= \beta_{10j} + \Gamma_{1ij} \\ \pi_{2ij} &= \beta_{20j} \\ \pi_{3ij} &= \beta_{30j} + \Gamma_{3ij} \\ \pi_{4ij} &= \beta_{40j}\end{aligned}$$

At Level 3, we entered adolescent oral contraceptive use (0 = *no*, 1 = *yes*), age, pubertal development, and nicotine use (number of cigarettes per day) as covariates (centered on the sample mean) that predicted the adolescent cortisol intercept (β_{00}) and adolescent cortisol slope (β_{30}):

$$\begin{aligned}\beta_{00j} &= \gamma_{000} + \gamma_{001}(\text{Adolescent Oral Contraceptives})_j + \gamma_{002}(\text{Adolescent Age})_j + \\ &\gamma_{003}(\text{Adolescent Puberty})_j + \gamma_{004}(\text{Adolescent Nicotine})_j \\ \beta_{10j} &= \gamma_{100} + U_{10} \\ \beta_{20j} &= \gamma_{200} \\ \beta_{30j} &= \gamma_{300} + \gamma_{301}(\text{Adolescent Oral Contraceptives})_j + \gamma_{302}(\text{Adolescent Age})_j + \\ &\gamma_{303}(\text{Adolescent Puberty})_j + \gamma_{304}(\text{Adolescent Nicotine})_j + U_{30} \\ \beta_{40j} &= \gamma_{400}\end{aligned}$$

In sum, this model yields the direct association between mother and adolescent cortisol levels, while accounting for effects of the diurnal rhythm of cortisol (Level 1), within-day correlated error in cortisol due to cortisol samples being nested in days (Level 2), and previously identified important demographic and health control variables (Level 3). As the γ_{100} parameter in Table 3 indicates, mother cortisol was positively associated with adolescent cortisol, beyond any shared association between them due to timing of the sample, the diurnal rhythm of cortisol,

within-day correlated error, or the control variables.¹ In addition, significant variance in this association was documented, $\sigma^2_{10} = 0.046$, $\chi^2 (df = 43) = 90.23$, $p < .001$, indicating that moderators warrant investigation.

Moderators of Mother-Adolescent Physiological Synchrony

To address our hypotheses concerning family and adolescent characteristics as moderators of the documented presence of mother-adolescent physiological synchrony, we conducted variants of the 3-level HLM described above with each potential moderator entered in Level 3 as an independent predictor of the mother-adolescent cortisol linkage (β_{10j}):

$$\beta_{10j} = \gamma_{100} + \gamma_{110} (\text{Synchrony Moderators}) + U_{10}$$

As shown in Table 4, the addition of the Level 3 moderators of synchrony revealed that adolescents' spending a greater proportion of their time with mother marginally strengthened mother-adolescent cortisol synchrony. Mother-adolescent cortisol synchrony was also significantly stronger among adolescents who engaged in higher levels of shared activities with parents and among adolescents who reported higher levels of parental monitoring and supervision (see Table 4). However, mother-adolescent cortisol synchrony was not moderated by adolescent perceived level of maternal attachment. Youths' pubertal development and gender did not moderate the positive mother-adolescent cortisol linkage, indicating that within-family physiological synchrony was robust across these youth characteristics.

We next tested interactions between parent-child relationship characteristics and adolescent characteristics as moderators of mother-adolescent cortisol synchrony. For these models, the centered terms and respective interactions were entered as predictors of the mother-adolescent cortisol linkage (β_{10j}) simultaneously in Level 3 (Aiken & West, 1991). Significant ($p < .05$) interaction terms were probed following Holmbeck's (2002) guidelines. HLM results showed that certain family characteristics interacted with adolescent pubertal development but not gender to moderate the mother-adolescent cortisol linkage. Specifically, youths' engaging in shared activities with parents and puberty interacted ($\gamma_{103} = 0.226$, $t = 2.58$, $p = .014$); post-hoc probing indicated that parental shared activities significantly strengthened mother-adolescent cortisol synchrony for adolescents reporting more advanced pubertal development ($\gamma_{101} = 0.277$, $t = 2.82$, $p = .008$), but not for adolescents reporting less advanced pubertal development ($\gamma_{101} = 0.027$, $t = 0.50$, $p > .05$). In addition, HLM results showed that parental monitoring and supervision interacted with pubertal development ($\gamma_{103} = 0.137$, $t = 2.33$, $p = .025$); post-hoc probing indicated that parental monitoring and supervision significantly strengthened mother-adolescent cortisol synchrony for adolescents more advanced on pubertal development ($\gamma_{101} = 0.145$, $t = 3.01$, $p = .005$), but not for adolescents less advanced on pubertal development ($\gamma_{101} = -0.006$, $t = -0.13$, $p > .05$). Taken together, the HLM results examining person-level moderators of cortisol synchrony suggest that family characteristics that reflect parent-adolescent closeness (i.e., spending more time together, engaging in activities together, and parental monitoring and supervision) strengthen the positive mother-adolescent cortisol linkage, and that more advanced pubertal development amplifies the effects of family closeness on within-family physiological synchrony.

Momentary Experiences as Underpinnings of Mother-Adolescent Physiological Synchrony: Presence of Mother, Positive Affect, and Negative Affect

To examine whether naturalistic, momentary experiences at the time of each diary report/saliva sample accounted for or moderated the documented mother-adolescent physiological synchrony, we next added simultaneously adolescents' reports of mothers' presence mother,

maternal momentary affective experiences, and adolescent momentary affective experiences to Level 1 of the synchrony model (see Table 3):

$$\text{Adolescent Cortisol}_{ij} = \pi_{0ij} + \pi_{1ij}(\text{Mother Cortisol})_{ij} + \pi_{2ij}(\text{CAR})_{ij} + \pi_{3ij}(\text{Time})_{ij} + \pi_{4ij}(\text{Time}^2)_{ij} + \pi_{5ij} \dots \pi_{9ij}(\text{Mother Presence and Momentary Affect Variables})_{ij} + e_{ij}$$

HLM results indicated that mothers' presence was related to lower levels of adolescent cortisol, although the mother-adolescent cortisol synchrony parameter remained significant (see Table 5), such that the presence of the mother did not account for mother-adolescent cortisol synchrony. Results indicated that mothers' and adolescents' negative and positive affect composites were not directly associated with adolescent cortisol when included in the synchrony model (see Table 5).

We next tested whether mothers' presence, maternal emotions, and adolescent emotions moderated mother-adolescent cortisol synchrony by adding centered variables of mother presence, maternal emotions, adolescent emotions; centered mother cortisol; and their respective interaction terms simultaneously to Level 1 of the synchrony model. The mothers' presence by mothers' cortisol interaction was not a significant predictor of adolescent cortisol levels (see Table 5). Thus, the physical presence of mother neither accounted for nor strengthened within-family physiological synchrony. Turning to mother and adolescent negative emotions, as shown in Table 5, mother cortisol interacted with both mother negative affect and adolescent negative affect in the prediction of adolescent cortisol. Probing the significant interactions indicated that the linkage between mother and adolescent cortisol was significantly stronger at moments of higher mother negative affect ($\gamma_{400} = 0.278, t = 3.47, p = .002$) than at moments of lower mother negative affect ($\gamma_{400} = 0.141, t = 2.32, p = .025$), and at moments of higher adolescent negative affect ($\gamma_{400} = 0.304, t = 3.90, p < .001$) than at moments of lower adolescent negative affect ($\gamma_{400} = 0.115, t = 1.54, p > .05$). Maternal and adolescent positive affect did not moderate the mother-adolescent cortisol linkage (see Table 5), indicating that family members' positivity has little bearing on mother-adolescent physiological synchrony in naturalistic contexts. In sum, results from the momentary diary data collected along with cortisol indicated that physical presence of mother lowered adolescent cortisol, but did not account for cortisol synchrony. Mother-adolescent cortisol synchrony was significantly stronger at moments throughout the day when both mothers and adolescents reported higher levels of negative affect (e.g., angry, frustrated, worried).

Discussion

This study is among the first to document associations between parent and child physiological processes as they occur in family members' naturalistic settings. As predicted, our results indicated mother-adolescent physiological synchrony -- net of the effects of the diurnal rhythm of cortisol -- by showing significant linkages between mothers' and children's cortisol levels as sampled 7 times across the day for two days. The results from tests of parent-child relationship characteristics as moderators align with other research that indicates that family environments play an important role in youth physiological functioning. As an example, using a twin design, Schreiber et al. (2006) showed that resemblance in family members' afternoon cortisol levels was accounted for by underlying shared environmental but not genetic characteristics. We examined family characteristics of proportion of time spent with mother and adolescents' perceptions of the parent-child relationship as moderators of mother-youth physiological synchrony, and found that proportion of time spent together (marginal), engagement in shared activities with parents, and parental monitoring and supervision strengthened the mother-adolescent cortisol linkage. Taken together, parenting characteristics that underpin family members' increased connections to each other through knowledge,

awareness, and shared experiences facilitate stronger within-family physiologic synchrony. Our examination of adolescent characteristics indicated that mother-adolescent cortisol synchrony did not vary as a function of adolescents' gender or pubertal development, although replication in future studies with larger samples of boys and girls who represent a wide age range is needed.

Interestingly, pubertal development interacted with family characteristics to moderate within-family physiological synchrony. Specifically, among youths' showing more advanced pubertal development, the positive mother-adolescent cortisol linkage was amplified for youths who reported that they engaged in more shared activities with their parents and rated their parents higher on parental monitoring and supervision. It is possible that puberty strengthens family moderating effects because adolescents showing more advanced pubertal development share more similar daily waking and schedule patterns with their parents. To address this possibility, we conducted post-hoc analyses and found that neither child age nor puberty was related to mother-child waketime similarity. In addition, mother-youth cortisol synchrony and the moderating effect of puberty were not accounted for by similarity in mothers' and adolescents' waketimes, suggesting that the amplified moderating effects on parent-adolescent synchrony found among youths showing more advanced pubertal development is not explained by corresponding schedules alone. Whether maturation of the HPA axis occurs with pubertal development, in ways that bring adolescent HPA axis function more closely in line with adult (parental) HPA axis function, remains to be determined in future studies – certainly, there is some evidence that changes in basal HPA axis activity, and HPA axis reactivity, seem to occur over the course of pubertal development (Adam, 2006; Stroud, Papandonatos, Williamson, & Dahl, 2004).

Our findings based on the momentary ESM data indicate that adolescents' cortisol was lowered at moments in which mothers were present. However, being together did not account for or amplify within-family physiological synchrony. Whereas mother and adolescent positive affect and negative affect were not directly linked to youth cortisol levels, both maternal and youth negativity amplified within-family physiological synchrony. That is, the mother-adolescent cortisol link was stronger among moments in which mothers and adolescents reported greater negative affect (i.e., frustrated, competitive, stressed, worried, strained, irritated, nervous, lonely, angry). The fact that this occurs for negative affect is not surprising, given that the HPA axis seems to be more responsive to negative rather than positive affective states (Adam, 2006; Dickerson & Kemeny, 2004). Nonetheless, these findings support an interplay between affectivity and physiological synchrony within families that awaits further explication in subsequent research.

Implications of the Present Study

Considering the results from the tests in which we examined family characteristics moderating synchrony as well as the results regarding momentary experiences (i.e., mother presence, mother and adolescent affective states) jointly tells an interesting (but complicated) story. Overall, mother-adolescent cortisol synchrony is stronger in adaptive family contexts. That is, when youth spend more time with parents, report higher engagement in shared activities with parents, and rate parents higher on monitoring and supervision behaviors, they have stronger physiological (or at least HPA axis) synchrony. However, cortisol synchrony is stronger at particular moments of higher negative emotions (i.e., mother and adolescent negative affect), suggesting that when one family member is experiencing stress or family members are engaged in conflict, that emotion and the physiological arousal accompanying it is shared by other family members. Thus, socially close families are more likely to experience concurrent physiological (HPA) arousal, and that shared physiological arousal is likely to occur at times that family members are experiencing negative affective states. In the short term, elevated

negative moods and the physiological changes that go along with them may be adaptive in motivating all family members to resolve negative situations and moods – one could even say this is reflective of empathic processes within families. In the long term, however, if socially close families are experiencing frequent stressors and are frequently co-activating each others' emotionality and/or physiology, their negative affect could become physiologically costly. Clearly, the question of whether HPA axis synchrony is a positive, adaptive sign of effective family functioning, and/or whether it is costly over the long-term for emotional and physical health outcomes (McEwen, 1998), remains to be determined in future longitudinal research.

Along similar lines, recent research (Davies et al., 2007; Pendry & Adam, 2007) explicated the interplay between marital functioning and youth cortisol, yet questions concerning the role of the marital relationship in mothers' and fathers' physiological functioning remain. Linkages found in the present study encourage researchers to incorporate parent cortisol in relation to child and parent physiological and psychological well-being, thereby capturing family-wide pathways linking emotional, physiological, and social domains. Such comprehensive views of family functioning are especially encouraged in light of recent calls to identify how physiological data may be used to advance treatment and prevention of parents' and children's psychopathology (Adam, Sutton, Doane, & Mineka, 2008).

Limitations and Future Directions

The present findings should be interpreted in the context of several methodological limitations. First, our data did not include naturalistic cortisol samples from a large enough sample of fathers to allow sufficiently powered father-adolescent analyses or family-level analyses (Maas & Hox, 2005). Our results based on a subset of families that included fathers' cortisol data ($n = 23$) provided preliminary evidence that parent-youth physiological synchrony for mothers versus fathers may be more similar than different. Subsequent testing of father-adolescent models, and full family models, examining not just dyadic but triadic processes or beyond (in the case of multiple siblings or the presence of extended family), is a necessary next step. Such models would allow tests of whether youth and family characteristics differentially moderate intra-familial physiological synchrony.

Second, there is a need to replicate the present findings in families who are diverse along race/ethnicity and family structure characteristics. The present study was largely comprised of European American youths who resided with two employed parents. Thus, additional research is needed to determine whether within-family physiologic synchrony replicates across a diverse array of family structures (e.g., single-parent or multi-generational households), ethnicities, and employment patterns. As an example, among families with parents who hold different employment schedules (e.g., shift-work) that limit daily time spent with the adolescent in the household, parent-child physiological synchrony might be expected to be weakened, especially to the extent certain parenting qualities of spending time together, engaging in shared activities, and providing monitoring and supervision are also limited.

Third, regarding the direction of effects of the linkages documented here, given that we did not have longitudinal data over a period of months or years, but rather two days of data, we are not able to discern whether closer family relationships lead to more connected physiological processes over time or whether linked physiological processes promote subsequent closer emotional and involvement ties. We also cannot determine whether the synchrony between maternal and adolescent stress hormone levels within the day is due to adolescent mood and related stress system activation influencing parent experiences and physiology, or whether parent mood and related physiological activation influence adolescent mood and stress, or whether joint or shared experiences simultaneously determine adolescent and maternal affective and physiological states. Perhaps more likely is the possibility that a dynamic interplay occurs between family affective, physiological, and relationship processes, whereby

over time family members' affect, physiology, and relationships exert dynamic influences on one other. This hypothesis awaits testing using longitudinal family data. Notwithstanding these limitations, the present study contributes to our understanding of within-family physiological synchrony and encourages the continued investigation of family processes in relation to parents' and children's physiological functioning.

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Table 1

Correlations among Adolescent and Family Characteristics

	1	2	3	4	5	6	7
1. Adolescent puberty	--						
2. Adolescent age	.37*	--					
3. Adolescent gender	-.38*	-.20	--				
4. Mother-adolescent time together	-.10	-.08	-.02	--			
5. Parent-adolescent shared activities	-.03	-.08	-.07	.24	--		
6. Parental monitoring and supervision	-.18	-.52**	.24	.05	.32*	--	
7. Adolescent perceived attachment to mother	.21	.15	-.03	.08	.38*	-.13	--

Note. Results are based on 45 mother-adolescent dyads. For gender, females are coded as 0 and males are coded as 1.

* $p < .05$.

** $p < .01$.

Table 2

Descriptive Statistics (untransformed, $\mu\text{g/dl}$) and Intercorrelations of Mothers' and Adolescents' Cortisol Values at Specific Sampling Points across the Two Sampling Days

Sample	Mothers		Adolescents		Mother-Adolescent Correlation	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>r</i>	<i>r</i>
1 (wakeup)	0.55	0.26	0.56	0.28	.25	
2	0.73	0.37	0.76	0.34	.46*	
3	0.23	0.19	0.26	0.18	.29†	
4	0.20	0.12	0.19	0.11	.29†	
5	0.13	0.10	0.18	0.11	.16	
6	0.10	0.09	0.11	0.07	-.07	
7 (bedtime)	0.11	0.15	0.10	0.17	.27*	

Note. Results are based on 45 mother-adolescent dyads.

† $p \leq .07$.

* $p < .05$.

Table 3

Hierarchical Linear Model of the Association between Mother Cortisol and Adolescent Cortisol: Physiological Synchrony Accounting for Diurnal Rhythm and Control Variables

Fixed effect	Coefficient	SE	<i>t</i>	Interpretation
Adolescent cortisol intercept (wakeup), π_0, β_{00}				
Intercept, γ_{000}	-0.625	0.076	-8.19**	$\hat{Y}_{\text{wakeup}} = 0.54 \mu\text{g/dl}^a$
Adol. oral contraceptives, γ_{001}	-0.196	0.143	-1.37	<i>n.s.</i>
Adolescent age, γ_{002}	-0.012	0.036	-0.34	<i>n.s.</i>
Adolescent puberty, γ_{003}	0.169	0.096	1.76 [†]	+18%/ scale point ^b
Adolescent nicotine, γ_{004}	0.0001	0.003	0.04	<i>n.s.</i>
Mother cortisol, π_1, β_{10}				
Synchrony intercept, γ_{100}	0.214	0.058	3.66**	+24% in adolescent cortisol for every 1 <i>SD</i> increase in maternal cortisol ^b
Cortisol awakening response (CAR), π_2, β_{20}				
Intercept, γ_{200}	0.380	0.109	3.49**	+46% if CAR ^b
Time since waking, π_3, β_{30}				
Intercept, γ_{300}	-0.120	0.018	-6.60**	-11%/h at waking ^b
Adol. oral contraceptives, γ_{301}	0.060	0.015	4.07**	+6%/h if use ^b
Adolescent age, γ_{302}	0.002	0.005	0.42	<i>n.s.</i>
Adolescent puberty, γ_{303}	-0.034	0.014	-2.47*	-3%/h per scale point ^b
Adolescent nicotine, γ_{304}	0.001	0.0003	4.59**	+0.1%/h per cigarette/day ^b
Time since waking ² , π_4, β_{40}				
Intercept, γ_{400}	0.001	0.001	1.00	<i>n.s.</i>

Note. Results are based on 45 mother-adolescent dyads.

^aDue to the logarithmically-transformed outcome variable (i.e., natural log of cortisol values), the inverse function of that transformation (i.e., exponential function) was applied to return this intercept to its value on its original scale of measurement.

^bSpecial properties of a logarithmic outcome variable allow coefficients predicting that outcome to be interpreted as % change in the outcome per unit change in the independent variable, after the following transformation has been applied to the *B* coefficient: $B\%$ change = $[\exp(B_{\text{raw}})] - 1$.

[†] $p < .08$.

* $p < .05$.

** $p < .001$.

Table 4
 Adolescent and Family Characteristics as Moderators of the Association between Mother Cortisol and Adolescent Cortisol (Physiological Synchrony) Accounting for Cortisol's Diurnal Rhythm and Control Variables

Fixed effect	Coefficient	SE	t	p	Compare model fit ^a
1. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.214	0.058	3.68	.001	
Adolescent gender, γ_{101}	0.005	0.052	0.09	> .05	$\chi^2 = 0.002$
2. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.214	0.057	3.77	.001	
Pubertal development, γ_{101}	-0.011	0.100	-0.11	> .05	$\chi^2 = 0.003$
3. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.210	0.059	3.55	.001	
Mother-adol. time together, γ_{101}	0.312	0.163	1.91	.062	$\chi^2 = 2.68^{\dagger}$
4. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.244	0.055	4.43	< .001	
Parent-adol. shared activities, γ_{101}	0.149	0.070	2.11	.041	$\chi^2 = 4.52^*$
5. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.235	0.055	4.29	< .001	
Parental monitoring/supervision, γ_{101}	0.093	0.040	2.32	.023	$\chi^2 = 4.61^*$
6. Mother cortisol, π_1, β_{10}					
Synchrony intercept, γ_{100}	0.212	0.059	3.62	.001	
Perceived mother-adolescent attachment, γ_{101}	0.060	0.067	0.90	> .05	$\chi^2 = 1.28$

Note. Results are based on 45 mother-adolescent dyads. Models retain Level 1 predictors and control variables included in the synchrony model shown in Table 3. Synchrony intercept reflects the strength of the interrelation between mother cortisol and adolescent cortisol levels over the two days of testing. Moderators were tested independently.

^a Significant ($p < .05$) chi-squared test with $df = 1$ indicates improvement in model specification when moderator was added to the synchrony model shown in Table 3.

[†] $p < .10$.

* $p < .05$.

Table 5

Association between Mother Cortisol and Adolescent Cortisol (Physiological Synchrony): Direct and Moderating Effects of Momentary Characteristics of Mother Presence, Mother Affect, and Adolescent Affect

Fixed effects: Main effects	Coefficient	SE	<i>t</i>	<i>p</i>
Mother cortisol ^a	0.191	0.063	3.04	.004
Presence of mother ^a	-0.068	0.025	-2.77	.009
Mother positive affect ^a	-0.024	0.049	-0.48	> .05
Mother negative affect ^a	-0.019	0.076	-0.25	> .05
Adolescent positive affect ^a	-0.026	0.065	-0.40	> .05
Adolescent negative affect ^a	0.055	0.074	0.75	> .05

Fixed effects: Interactions with mother cortisol	Coefficient	SE	<i>t</i>	<i>p</i>
Presence of mother ^b	0.075	0.074	1.01	> .05
Mother positive affect ^b	-0.026	0.050	-0.53	> .05
Adolescent positive affect ^b	-0.077	0.058	-1.32	> .05
Mother negative affect ^b	0.143	0.067	2.14	.033
Adolescent negative affect ^b	0.169	0.076	2.24	.026

Note. Results are based on 45 mother-adolescent dyads. Models retain Level 1 predictors and control variables included in the synchrony model shown in Table 3. Predictors with the same superscripts were entered simultaneously.