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Family Stress Moderates Relations between Physiological and Behavioral Synchrony and Child Self-Regulation in Mother-Preschooler Dyads

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Abstract

From a bio-behavioral framework, the relations between physiological synchrony, positive behavioral synchrony, and child self-regulation under varying levels of risk were examined among 93 mother-(*M* age = 30.44 years, *SD* = 5.98 years) preschooler (*M* age = 3.47 years, *SD* = .52 years, 58.70% male) dyads. Physiological synchrony was examined using Interbeat Interval (IBI) data and measures of positive behavioral synchrony and self-regulation were based on observations of a mother-child interaction task. Results supported the phenomenon of physiological synchrony among mother-preschooler dyads during an interaction, but not a baseline, task. Moderation analyses indicated that under conditions of high family risk, positive behavioral synchrony and child self-regulation were greater when physiological synchrony was low. Positive behavioral synchrony was positively associated with child self-regulation, regardless of risk status. The results document physiological synchrony among mothers and their preschool-aged children and the complex ways that physiological attunement relates to important developmental processes.

Keywords

synchrony; risk; self-regulation; parent-child interaction; preschool

Self-regulation, the ability to regulate behavior and emotions in response to environmental demands, is foundational for adaptive development. Early self-regulatory processes relate to important indices of psychosocial adjustment ranging from academic success to social skills (Calkins & Keane, 2004; Graziano, Reavis, Keane, & Calkins, 2007), and the failure to develop appropriate self-regulatory capacities has been linked to multiple types of maladjustment throughout development (Bradley et al., 2011; Portilla, Ballard, Adler, Boyce, & Obradović, 2014). The developmental process of self-regulation begins in the context of the parent-child relationship, and the relationship itself serves key functions that can either facilitate or impede healthy child self-regulation (Moore & Calkins, 2004; Fay-Stammbach, Hawes, & Meredith, 2014; Feldman, 2007b; Feldman, Greenbaum, & Yirmiya, 1999; Posner & Rothbart, 2000). Positive behavioral synchrony among parents and children, which consists of mutual cooperation, reciprocity, and harmony (Harrist & Waugh, 2002)

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has been identified as an important component of the parent-child relationship, and has been related to children's self-regulation development (Kochanska, Aksan, Prisco, & Adams, 2008).

Much less is known about the ways that physiological synchrony, or the matching of biological states among parents and children, relates to child self-regulation. Yet, according to theoretical work on bio-behavioral synchrony "discrete biological and behavioral events synchronize into a unified experience" (Feldman, 2012, p. 155). While physiological synchrony may emerge first, even prenatally, the processes are likely mutually influential in the early years of child development, and the ways in which they interact are poorly understood. Nonetheless, research has demonstrated the co-occurrence of behavioral and biological synchrony across physiological systems (Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011; Ham & Tronick, 2009), therefore indicating that it is important to study synchrony across multiple levels of analysis. Collectively, studying behavioral and physiological forms of synchrony in tandem as they relate to child self-regulation is important for advancing developmental models of youth self-regulation.

This study examined relations between physiological synchrony, positive behavioral synchrony, and child self-regulation, in the context of family risk. Across contexts, positive behavioral synchrony among caregivers and children has been associated with adaptive child outcomes (e.g., Criss, Shaw, & Ingoldsby, 2003; Kochanska & Kim, 2014; Laible & Thompson, 2000). However, physiological synchrony may or may not be desirable, depending on the context in which it occurs. High physiological synchrony suggests that partners are closely attuned to one another. In the context of higher levels of family risk (e.g., socioeconomic disadvantage, parental psychopathology), individual family members are likely to experience greater levels of negative emotion. Physiological synchrony under such conditions may be undesirable because it may exacerbate already high levels of negative emotions, which may become overwhelming to the child and interfere with the ability to self-regulate. Likewise, high physiological synchrony in the context of family risk may interfere with behaviors known to facilitate child self-regulation (e.g., coordinated and cooperative responses, positive exchanges). Thus, examining relations among positive behavioral synchrony, physiological synchrony, and child self-regulation under conditions of risk is important. Youth from economically disadvantaged backgrounds may be at particular risk for poor self-regulation development (Evans & English, 2002; Lengua, Honorado, & Bush, 2007; Li-Grinning, 2007; Mezzacappa, 2004) given that socioeconomic disadvantage is associated with other family risk factors (e.g., maternal depression, household density) that may compromise the development of healthy parent-child relationships (Conger et al., 1992; Evans, 2003). Specifically, both maternal (depression, anxiety) and infant (preterm birth, intrauterine growth retardation) risk factors have been found to disrupt the process of behavioral synchrony (Feldman, 2007a). Consequently, it is likely that the quality of parent-child physiological synchrony, and, therefore, the relation between physiological synchrony and child self-regulation, is impacted by family risk status.

Parent-Child Synchrony and Child Self-Regulation in Preschoolers

Developmentally, as children transition from infancy and dependence on parents for regulation to greater independence in self-regulation during the preschool years (Kopp, 1982), this period represents an intriguing transition point for studying the implications of physiological and behavioral synchrony. During infancy, regulatory processes are almost entirely parent-dependent; thus, positive behavioral synchrony in this developmental period is often a sign that a parent is reading an infant's cues correctly rather than representing an actual coordinated exchange that is equally driven by parent and child (Feldman, et al., 1999; Tronick & Cohn, 1989). In early childhood, self-regulation becomes a more dyadic process (Harrist & Waugh, 2002); though the child is generally not capable of self-regulation completely independent of parental support, he or she can more independently signal for assistance when needed and respond cooperatively.

Most research on the links between parent-child synchrony and child self-regulation has focused on behavioral indices of synchrony. However, the consideration of a child's broader biopsychosocial context when studying child adjustment and maladjustment can help to better capture the complexity of critical developmental processes (Calkins, Propper, & Mills-Koonce, 2013). Moreover, the notion of bio-behavioral synchrony (Feldman, 2012) highlights the interconnection between biological and behavioral forms of synchrony and the need to measure synchrony across multiple levels of analysis. Therefore, in order to best understand the relation between parent-child synchrony and child self-regulation, it is crucial to include a multi-method assessment of synchrony that takes into account both biological and behavioral processes.

Given the importance of early childhood for the emergence of self-regulatory abilities, research has examined positive behavioral synchrony and links to self-regulation during the toddler and preschool years (Kochanska, 1997; Kochanska & Kim, 2014; Lay, Waters, & Park, 1989; Raver, 1996; Spinrad et al., 2012). For instance, Laible and Thompson (2000) found that shared positive affect between mothers and their preschool-age children was related to committed compliance (i.e. diligently following requests to clean a playroom without relying on maternal control). Kochanska and colleagues have examined positive behavioral synchrony as a "mutually responsive orientation" (MRO; Kochanska, 1997), which generally reflects a positive, reciprocal interaction between parent and child where partners are attuned to each other behaviorally and emotionally. In an earlier study, Kochanska (1997) found that MRO at ages 21–41 months predicted less maternal use of power and greater internalization of maternal rules when the children were approximately 13 months older. Later, Kochanska et al. (2008) found that maternal power assertion fully mediated the relation between MRO at 7, 15, and 25 months and child internalization of parent rules at 52 months and partly mediated the positive effects of MRO on child self-regulation. Paternal-child MRO predicted child self-regulation and paternal power assertion was negatively associated with both child self-regulation and the internalization of rules. More recently, Hinnant and colleagues have presented evidence among school-aged children that observed mother-child cooperative behavior is associated with child emotion regulation (Hinnant, Nelson, O'Brien, Keane, & Calkins, 2013).

Though parent-child positive behavioral synchrony has clear implications for youth development, how *physiological synchrony* (i.e., the matching of biological states between parents and children) operates during the preschool period and relates to positive behavioral synchrony and child self-regulation is unclear. Physiological synchrony has been assessed at several points throughout the developmental spectrum; however, and via a variety of biological indices, including cardiovascular activity (Feldman et al., 2011; Moore, 2009), adrenocortical functioning (Williams et al., 2013) and skin conductance (Ham & Tronick, 2009). For instance, Zelenko et al. (2005) created a consistency index between maternal and child heart rate changes to reflect the degree to which maternal and child heart rate changed in tandem across baseline, separation, and reunion tasks. Results indicated that consistency in heart rate changes was higher among secure mother-infant dyads than insecure-resistant dyads. In another study, Papp, Pendry, and Adam (2009) found that maternal and adolescent cortisol levels were positively associated and that the relation was strengthened when either the mother or adolescent reported greater negative affect. Similarly, Laurent, Ablow, and Measelle (2012) found that increases in mothers' cortisol across the course of a social stress session predicted greater cortisol responses among their 18-month-old infants. Laurent et al. (2012) also found that increases in maternal salivary alpha-amylase reactivity, an index of sympathetic nervous system activation, predicted children's increases in salivary alpha-amylase reactivity. In comparing the two stress tasks, higher levels of mother-child cortisol synchrony were observed during the Strange Situation task. Alternatively, during a challenge stress session, which involved a free-play/cleanup task prior to a series of lab tasks meant to elicit children's emotions, greater salivary alpha amylase synchrony was found. Collectively, the studies document the phenomenon of physiological synchrony across a variety of systems and in both low- and high-stress contexts. Though synchrony occurs across a variety of physiological systems, it is unknown whether such synchrony is all part of the same process.

Importantly, while cardiovascular concordance has been documented in mother-child dyads during the preschool period (Creaven, Skowron, Hughes, Howard, & Loken, 2014), no known studies have assessed moment-to-moment physiological synchrony in this age group. Because physiological synchrony likely unfolds in a moment-to-moment fashion, indices of synchrony that rely on averages of mother and child physiological functioning across a specified timeframe may not fully capture the intricacies of parent-child physiological synchrony. In the same vein, physiological measures that require data to be collected after a specific situation has ended (e.g., cortisol samples taken following a stressor task) do not provide information on how physiological synchrony occurs in real-time. Temporal synchrony of autonomic reactivity can be measured via Interbeat Interval (IBI) series data, which allows for a nuanced approach for assessing physiological concordance across hundreds of data points within a short time period. Given that research has linked mother-child positive behavioral synchrony to important developmental outcomes, it is crucial to delineate how physiological synchrony relates to similar indices of child adjustment using methodologically-rigorous approaches.

Family Risk as a Moderator

The differential relations of physiological synchrony to developmental correlates based on family context are largely unexplored in the empirical literature at this point. Most research has focused on describing the conditions under which physiological synchrony can be observed rather than exploring ways that this synchrony relates to indices of children's psychosocial functioning, thereby further highlighting the novelty of the present study. Nonetheless, researchers have hypothesized about the potential long-term implications of physiological synchrony that occurs in the context of shared negative emotions, suggesting that such synchrony may negatively impact later emotional and physical functioning (e.g. Papp et al., 2009). Drawing from literature on children of depressed mothers, research suggests that these children have similar psychophysiological profiles to their depressed mothers, which include, but are not limited to, lower vagal tone and greater relative right frontal electroencephalography activation compared to offspring of non-depressed mothers (e.g., Field et al., 2004). In light of the many adverse outcomes found among offspring of depressed mothers (e.g., Goodman et al., 2011), it is likely that physiological concordance in the context of mothers' high levels of negative emotion can signify risk for maladaptive youth outcomes. In contrast; however, Ebisch et al. (2011) found concordance in autonomic responses among preschool-aged children and their mothers during a situation designed to elicit child distress. The authors concluded that concordance in autonomic reactivity may underlie maternal empathic responding, which is necessary for a secure attachment relationship. Moreover, the ability to maintain positive behavioral synchrony in the midst of a distressing situation may indicate the presence of a "strong empathic connection" that manifests itself at the physiological level as well (Woltering, Lishak, Elliott, Ferraro, & Granic, 2015). The studies collectively demonstrate the necessity of considering context when assessing links between physiological synchrony and developmental processes.

Though no studies examining moment-to-moment physiological synchrony during the preschool period could be found, a study by Creaven et al. (2014) demonstrated that the links between mothers' and preschoolers' physiological functioning, measured via heart rate and respiratory sinus arrhythmia (RSA), can vary based on family risk. Specifically, for dyads designated as "child-maltreating," between-dyad analyses (i.e., associations between maternal and child average levels of physiological reactivity) indicated that greater average maternal heart rate was related to greater child heart rate and lower RSA. Within-dyad analyses (i.e., examining the relation between changes in mothers' and children's physiological responses) demonstrated that mother and child heart rate was positively associated, but only for non child-maltreating dyads. Regardless of level of risk, negative within-dyad relations between maternal heart rate and child RSA were observed.

Additional research supports the notion that physiological synchrony is not uniformly associated with harmonious, close relationships under all conditions (Ham & Tronick, 2009; Levenson & Gottman, 1983) and that physiological synchrony may even confer further risk in the context of high stress. Ham and Tronick (2009) clearly demonstrated this point in comparing mother-infant skin conductance concordance during still-face and reunion play episodes. During the still-face episode, skin conductance concordance was related to indices of negative infant engagement (e.g., protesting, fussing; Ham & Tronick 2009). Thus, when typical parent-child exchanges are disrupted, physiological synchrony may not contribute to positive behavioral exchanges between the parent and child. On the other hand, skin conductance concordance during the reunion episode (i.e., when mothers were able to play with their children as they typically would) was related to mother-infant behavioral synchrony (Ham & Tronick, 2009). In a study by Levenson and Gottman (1983), high physiological synchrony (termed "physiological linkage") was greatest among distressed married couples during a problem-focused task. Further, physiological synchrony accounted for the greatest amount of variance in marital satisfaction.

Of note, studies of family risk sometimes focus on single risk factors. Yet, developmental research and theory suggest that the nature of familial risk is rarely specific to one or two risk factors, and empirical evidence indicates that the cumulative nature of risks "piling up" in the family environment can be a more potent statistical, as well as experiential, way to predict maladaptive outcomes (Sameroff, 2006; Masten, 2001). The use of aggregated risk indices is common in the developmental literature for this reason, and is utilized here as a method to identify family-level risk, broadly defined. We follow previous research (e.g., Barakat et al., 2007; Dawson-McClure, Sandler, Wolchik, & Milsap, 2004; Shaffer, Suveg, Thomassin, & Bradbury, 2012) in utilizing a risk index score as a moderator variable in order to test the role of family context in the relations between parent-child positive behavioral synchrony, physiological synchrony, and child self-regulation.

The Current Study

In sum, research strongly supports the notion that positive behavioral synchrony among preschoolers and parents facilitates important developmental processes, including self-regulation. Despite theory indicating the importance of examining biological and behavioral processes in tandem (Calkins et al., 2013; Feldman, 2012), the extant literature is limited in its examination of how biological and behavioral aspects of the mother-child relationship relate to each other and to child self-regulation.

The first goal of this study was to document that physiological synchrony occurs in mother-preschooler dyads during a behavioral observation task designed to reflect a typical parent-child interaction that occurs during the preschool period. We expanded upon the extant literature by conducting moment-to-moment analyses of physiological synchrony and by examining this synchrony at both high and low levels of activation. The second goal was to examine relations among physiological and behavioral synchrony and child self-regulation. In light of the influence of stress on parenting behaviors specifically (Newland, Crnic, Cox, & Mills-Koonce, 2013) and bio-behavioral development broadly (Schilling, Aseltine, & Gore, 2008; Shonkoff, Boyce, & McEwen, 2009), the interaction between synchrony (both physiological and behavioral) and family risk was tested to assess how the role of synchrony in developmental processes may vary across family contexts. A cumulative family risk index composed of variables known to confer risk for poor child outcomes either directly or indirectly through parenting behaviors (i.e., economic disadvantage, maternal psychological distress, single parent status, and education attainment of GED/high school diploma or less) was examined.

Based on the extant literature, we tested the following hypotheses:

1. Physiological synchrony would occur during a mother-preschooler interaction task at both high and low levels of physiological activation.
2. Family risk would moderate the associations between physiological synchrony, positive behavioral synchrony, and child self-regulation. Specifically, it was hypothesized that in the context of high levels of family risk, physiological synchrony would be negatively associated with positive behavioral synchrony and child self-regulation. In the context of low levels of family risk, physiological synchrony was expected to be positively related to positive behavioral synchrony and child self-regulation.
3. Given that extensive literature has linked parent-child positive behavioral synchrony to adaptive outcomes across contexts, it was expected that positive behavioral synchrony would be positively related to child self-regulation at both low and high levels of family risk.

Method

Participants

Participants included 93 biological mothers (*M* age = 30.44 years, *SD* = 5.98 years) and their preschool-age children (*M* age = 3.47 years, *SD* = .52 years, 58.70% male). This sample was part of a larger study that included genetics data collection and, therefore, only biological mothers and their children were included. Mothers and their children were required to be fluent in reading and speaking in English. Mothers were excluded if they were currently pregnant. Children with a developmental disability that would hinder their ability to fully participate in the lab visit were also excluded. In total, 9 families were unable to participate in the study due to the aforementioned exclusionary criteria.

The sample was diverse both racially and economically. Nearly half (47.30%) of mothers identified themselves as Black, 44.10% were Caucasian, 1.10% were Asian, 2.20% were Hispanic, and 5.40% identified themselves as “other.” 41.90% of families had a total household income of $0–$19,999; 20.40% of the sample was between $20,000 and $39,999; 18.30% was between $40,000 and $79,999; and 19.40% had a total income above 80,000. Almost half (45.20%) of mothers indicated they were currently married, 41.90% reported they had never been married, 3.20% were separated, 5.40% were divorced, 2.20% were widowed, and 2.20% were engaged. With regards to the mothers’ education levels, 1.10% of the mothers were junior high school graduates, 16.10% had their General Educational Development (GED) certificate, 12.90% were high school graduates, 22.60% had some college training, 26.90% were college graduates, and 20.40% had graduate school training.

Procedures

Packets of measures were mailed home for mothers to complete and then return on the day of their lab visit. Mothers who did not complete their forms beforehand did so at the lab visit. At the lab visit, mothers provided consent for their participation as well as permission for their child to participate and their children provided assent. Electrodes were next placed on the mother and child to collect IBI data for each of the structured behavioral observation tasks. Mothers and their children participated in a 4-minute baseline segment (i.e., sitting quietly) to allow them to acclimate to the electrodes. Afterwards, dyads were videotaped while they participated in an Etch-a-Sketch interaction task, which required the dyad to collaboratively draw a picture of a house using an Etch-a-Sketch in 4 minutes. For their participation in the larger study, parents were compensated $100 and children chose a small prize. Procedures used in the present study were all in accordance with the sponsoring university's Institutional Review Board.

Measures

Physiological synchrony

Interbeat interval series: Interbeat Interval (IBI) series data were collected during the Etch-a-Sketch task using MindWare BioLab Software (Version 3.0.6) and were analyzed with MindWare HRV Software (Version 3.0.25) (MindWare Technologies, Ltd., Gahanna, OH.). IBI data was chosen in particular to assess moment-to-moment synchrony (i.e., micro analysis of physiological synchrony). Disposable silver chloride electrodes were placed on the right collar bone (i.e., the right clavicle area), in the cleft of the throat (i.e., below the Adam's apple), at the base of the 10^{th} rib on the left and the right sides of the body, near the xiphoid process, midway down the spine, and about 2 cm below the base of the skull upon the back. The EKG signal was digitized at 1000 Hz and MindWare created an interbeat interval (IBI) series via a peak-identification algorithm.

To calculate IBI values (i.e., the time between heartbeats), an algorithm that relied on the peak of the R wave as the reference point was used. MindWare created 4 Hz time series based on the mother's and child's separate IBI series through the use of resampling at fixed intervals with interpolation (Berger, Akselrod, Gordon, & Cohen, 1986; Berntson, Cacioppo, & Quigley, 1995). The time series was linearly detrended using the second order polynomial in order to minimize nonstationaries in the data (Litvack, Overlander, Carney, & Saul, 1995). The Hamming window was used to taper the residual series and the time series underwent either a Discrete Fourier transformation (DFT) or a fast Fourier transformation (FFT) through the LabVIEW module (National Instruments, Austin, TX) to determine the spectral distribution. A radix-2 FFT was used if the number of data points was a factor of 2 whereas DFT was implemented in all other cases. The respiratory frequency band was set at .12–.4 Hz.

The Society for Psychophysiological Research Committee recommends that a minimum of 10 cycles of the rhythm of interest should be utilized for analyses (e.g., Berntson et al., 1997). Furthermore, the Committee specifies that for low frequency heart rate variability, a minimum of 2 minutes of recording should be used whereas for the high frequency band (e.g. RSA data), a minimum of 1 minute of recording is preferable. The present study relied on a minimum of 2 minutes of continuous IBI data for each participant, though a maximum of 3 minutes of IBI data was used for each participant. The last minute of each individual's 4-minute IBI series was excluded from subsequent analyses given that there was significantly more error during this period for mothers as compared to the previous three minutes of the task ($t(74) = 3.11$, $p < .01$). The fact that families were permitted to end the

Etch-a-Sketch task early if they finished drawing the house before the allotted time elapsed and were encouraged to complete the task quickly likely contributed to the relatively low amount of data from the last minute of the Etch-a-Sketch task that was analyzable across both mothers and children.

To detect artifacts, an algorithm within the MindWare software was used (Berntson, Quigley, Jang, & Boysen, 1990), in addition to visual scanning, prior to the manual removal of these data points. Data points were manually inserted on the correct R peaks when data points were removed as a result of the software's incorrect R peak identification, allowing for continuous series of IBI data to be available. Research assistants implemented this rigorous approach to data cleaning following extensive training from MindWare manufacturers. Only participants who had IBI series in which 10% or less of the data required editing across the specified number of segments were included in analyses, similar to criteria outlined in other research that has used related forms of psychophysiological data such as RSA (e.g., Blandon, Calkins, Keane, & O'Brien, 2010). Due to the dyadic nature of the analyses conducted in this study, both members of each dyad were required to have the same number of clean epochs, occurring at the same time within the task, to be included in the analyses. Using only clean segments that occurred at matching times resulted in a smaller sample size, but was necessary for accurately assessing the moment-to-moment temporal synchrony of each dyad. Details regarding the sample size are provided in the Missing Data section below.

Observational measures—The parent-child interaction task (i.e., Etch-a-Sketch) was coded by trained observers for indicators of child self-regulation and positive behavioral synchrony (listed below). These indicators were drawn from scales developed by the Minnesota Longitudinal Study of Parents and Children for observations of parent-preschooler dyads (Sroufe, Egeland, Carlson, & Collins, 2005); scales are available upon request. All scales were scored from 1 to 5, with higher scores indicating more positive functioning. To establish inter-rater reliability, a subset of 33 families was coded by two trained observers and intraclass correlations (ICCs) were computed to measure rater agreement. Reliability estimates for each scale are presented below.

Positive behavioral synchrony: This scale reflected the mother-child dyad's ability to work together effectively. Our definition of positive behavioral synchrony is largely based on the definition of synchrony put forth by Harrist and Waugh (2002), which states that synchrony is "an observable pattern of dyadic interaction that is mutually regulated, reciprocal, and harmonious" (p. 557). The term positive behavioral synchrony suggests that the overall tone of the interaction was positive (e.g., the dyad exhibited connectedness and reciprocity; Criss et al., 2003; Harrist, Pettit, Dodge, & Bates, 1994). Dyads high in positive behavioral synchrony cooperatively responded to one another's suggestions, actively contributed ideas, solicited one another's opinions regarding strategies for completing the task, and showed empathic responding to one another. In contrast, dyads low in positive behavioral synchrony failed to work together on tasks, redefined joint tasks as individual ones, and/or maintained an emotional and communicative distance. The particular components of synchrony that were coded were chosen because prior research has identified them as important aspects of the parent-child relationship for young children's development (e.g., Kochanska & Kim, 2014). Inter-rater reliability for this scale was good (ICC = 0.69 in the present study; Cicchetti, 1994).

Child self-regulation: This scale measured how focused and participatory the child was on the observed task. High scores on this scale reflected clear persistence throughout the task, even in the face of obstacles or frustration. A child high in self-regulation stayed focused on the task, even when not talking, and stayed with the task until it was completed. Low scores on this scale reflected consistent task disengagement, inattention, or disruptive/noncompliant off-task behaviors. Despite the fact that the parent may have been open to involvement on the part of the child, and may have actively tried to get the child involved, the child low in self-regulation did not comply. This child may have been inattentive, or even disruptive to the point of walking away from the task or trying to pull the parent away from working on the task. The child self-regulation code used in the present study encompassed aspects of effortful control, particularly attentional focusing, meaning the child's ability to maintain focus and persist during a task (Rothbart, Ahadi, Hershey, & Fisher, 2001). Inter-rater reliability for this scale was excellent (ICC = 0.80 in the present study; Cicchetti, 1994).

Family risk

Total family risk index: An index of family risk was created based on a composite of variables that are known to confer risk (single parent status, GED/high school diploma or less educational attainment, economic disadvantage, and maternal psychological distress) and was similar to scales used in previous research (e.g. Calkins, Blandon, Williford, & Keane, 2007; Shaffer et al., 2012). All items were assessed via maternal report. To measure mothers' current psychopathology symptoms, mothers completed the Symptom Checklist-90-Revised (SCL-90-R; Derogatis, 1994). For this study, the Global Stress Index was used; higher scores represent greater psychological distress. Previous research has indicated the SCL-90-R has adequate reliability and validity (Derogatis, 1994) and Cronbach's alpha for this study was 0.97.

In each of the four domains (marital status, household income, maternal education level, and psychological distress), families received a score of "1" if they were considered "high risk" in that specific domain. Single status (i.e., neither married nor engaged), household income less than $30,000, maternal education level of high school diploma/GED or less, and SCL-90-R Global Severity Index T score of 65 or greater were all considered "high risk." The total family risk index had a range of 0 to 4, with 4 indicating the highest level of risk. Mothers were required to have complete data for each of the indices assessed to receive a composite score.

Missing Data

In the total sample (N = 108), 71 mother-child dyads had usable data to run the moderation models involving physiological synchrony and 93 dyads had sufficient data to be included in the moderation model that examined family risk as a moderator of the relation between positive behavioral synchrony and child self-regulation. Several factors contributed to the missing IBI data (e.g., technological difficulties such as the loss of wireless connection during the task, failure of dyads to participate in the Etch-a-Sketch task, the rigorous data editing methods used). Missing data for the behavioral observation codes was due to technological difficulties that resulted in either a lack of video footage for the whole task or recordings that made it too difficult to see the participants for coding purposes, as well as protocol deviations (e.g., a sibling showed up to the assessment and sat at the table with the participating mother-child dyad). Additionally, two families chose not to participate in the Etch-a-Sketch task. Independent samples t-tests were run to determine if there were any significant differences between those with and without data for the main moderation models involving physiological synchrony with regard to maternal and child age. Similarly, chi-square tests were run for child sex and total household income and Fisher's exact tests were run for maternal race, maternal marital status, and maternal education level to examine whether there were significant differences in these demographic variables between included and excluded families. No significant differences were found for any of these variables.

Analytic Strategy

To examine synchrony, and thus test our first hypothesis, each individual's IBI series underwent Autoregressive Integrated Moving Average (ARIMA) modeling (Feldman et al., 2011). This procedure in particular was chosen because it allows for an examination of synchrony independent of the autocorrelation in each IBI series (Feldman et al., 2011). An overview of ARIMA modeling is provided here. For additional information on this procedure for analyzing synchrony, readers are referred to Feldman et al. (2011).

In the present study, because each individual's total IBI series was unique from the rest of the sample, SPSS Expert Modeler was used to identify the best fitting ARIMA model for each individual time series based on stationary R-squared. In light of the difficulty in reliably identifying ARIMA models, automated ARIMA modeling procedures have been both recommended and implemented in the extant literature (e.g., De Gooijer & Hyndman, 2006; Hyndman & Khandakar, 2007; Loha, & Lindtjørn, 2010). When necessary, SPSS Expert Modeler transformed time series variables through differencing, square root transformations and/or natural log transformations to achieve stationarity. Given the unique nature of each ARIMA model identified, some models contained all three components of an ARIMA (i.e., the auto-regressive, integrated, and moving average terms). However, in some instances it was possible that an individual's best-fitting model contained only one or two of these components (e.g., a model with an auto-regressive component but no integrated or moving average terms). Stationary R-squared was used to determine the best-fitting model since, when no transformations are performed, stationary R-squared and ordinary R-squared are equivalent. On the other hand, when trends or seasonality are present (i.e. transformations are needed), SPSS noted that stationary R squared is preferable to ordinary R-squared. The Ljung-Box Q statistic and/or plots of the residual autocorrelation functions (ACF) and partial autocorrelation functions (PACF) were examined to double-check the models identified by SPSS Expert Modeler. Expert modeler allowed for the visualization of up to 24 lags for the ACF and PACF plots.

Following procedures outlined in Feldman et al. (2011), the residuals of each ARIMA model were then used to calculate Cross Correlation Functions (CCFs) with no time lag for each mother-child dyad to examine the relation between the IBI series of both members of the dyad. Correlating the residuals of the individual ARIMA models, and thus removing the autocorrelated component of each time series, provided a measure of mother-child synchrony beyond each individual's time series (Feldman et al., 2011). Also, similar to Feldman et al. (2011), the distribution of all of the dyads' CCFs was compared to 0 using a one-sample t-test in order to conclude whether physiological synchrony was present.

Additional analyses were conducted to examine the second part of our first hypothesis (i.e., that physiological synchrony was likely to occur at both higher and lower levels of physiological activation). To answer this question, mean heart rate values for each second of data collection (the smallest time window of data MindWare will provide in a time-stamped format) were examined. Adapted procedures from those used in Feldman et al. (2011) were employed. To best capture the majority of the data, outliers were identified as those values that fell at 1 standard deviation above or below the individual's mean heart rate. Therefore, outliers represented significant spikes or declines in individuals' IBI data. These outliers were not removed but were rather used to describe the frequency of physiological synchrony at high and low levels of activation across the dyads. Dyads were examined for concordant increases or decreases in heart rate within a 10-second window (Feldman et al., 2011). The mean number of times that concordant changes in heart rate occurred for higher-synchrony (i.e., above the sample mean on physiological synchrony) families in the higher- and lower-risk (i.e., above and below the sample mean on the risk index, respectively) groups was then examined.

Before conducting our moderation analyses to test the second and third study hypotheses, the predictor variables were centered to reduce nonessential multicollinearity between the independent variable, moderator, and interaction term (Aiken & West, 1991). Moderation analyses were run using the publicly-available PROCESS SPSS macro plug-in (http://afhayes.com/introduction-to-mediation-moderation-and-conditional-process-analysis.html; Hayes, 2012). Moderation was evident when the interaction term between the predictor and the moderator variable was significant and the confidence interval did not include zero. We used 95% confidence intervals and the conditional associations between the independent and dependent variables were examined at low (−1 *SD* below the mean) and high (+1 *SD* above the mean) levels of the moderator variable (i.e., family risk). Models were tested separately for each dependent variable (i.e., child self-regulation and positive behavioral synchrony) when physiological synchrony was the independent variable. Moderation analyses were also conducted with positive behavioral synchrony as the independent variable and child self-regulation as the dependent variable.

Results

In support of our first hypothesis, the CCFs during the Etch-a-Sketch task were significantly different from 0, $t(79) = 2.42$, $p < .05$, indicating synchrony was present. For comparison, physiological synchrony was also examined during the baseline task. The CCFs for the baseline segment were not significantly different from 0, $t(74) = 1.32$, $p = .19$, suggesting that moment-to-moment mother-preschooler physiological synchrony is likely specific to interaction tasks.

Next, we tested whether physiological synchrony was observed at both high and low levels of physiological activation for higher- and lower-risk families. Results indicated that higher-risk (i.e., above the sample mean on the total family risk index) families that exhibited higher levels of physiological synchrony (i.e., above the sample mean for physiological synchrony) experienced an approximately equal number of instances of synchrony at both high (M = 13.12) and low (M = 12.94) levels of physiological activation. Similarly, lower-risk families that exhibited higher levels of synchrony demonstrated an approximately equal number of instances of synchrony at both high (M = 12.85) and low (M = 13.56) levels of physiological activation. Thus, these findings provide further support for hypothesis one.

In preparation for our moderation analyses, we examined relations between physiological synchrony (i.e. the CCFs), family risk, positive behavioral synchrony, and child self-regulation. Descriptive statistics for the main study variables are presented in Table 1 for families at higher (above the mean) and lower (below the mean) levels of family risk, respectively. Bivariate relations between physiological synchrony, positive behavioral synchrony, and child self-regulation were examined separately for families at higher and lower levels of family risk (see Table 2). When broken down by family risk levels, a significant, negative correlation between physiological and behavioral synchrony was found at higher levels of risk. Additionally, behavioral synchrony was significantly, positively related to child self-regulation for both higher- and lower-risk families.

In partial support of our second hypothesis, family risk significantly moderated the relation between physiological synchrony and positive behavioral synchrony (see Table 3 and Figure 1). The R^2 change due to the interaction term was .06. Simple slopes analyses yielded a significant conditional effect at high levels of family risk. Families experiencing greater levels of family risk demonstrated higher levels of positive behavioral synchrony when physiological synchrony was low than when it was high. There was no significant conditional effect at low levels of family risk (see Table 3).

Similarly, family risk significantly moderated the relation between physiological synchrony and child self-regulation (see Table 3 and Figure 2). The R^2 change due to the interaction term was .07. The simple slope was again significant at high, but not low, levels of family risk such that children from families experiencing greater levels of risk showed higher levels of self-regulation when physiological synchrony was low than when it was high.

Moderation analyses indicated that positive behavioral synchrony was significantly, positively related to child self-regulation at both low and high levels of family risk (see Table 4 and Figure 3). This suggests that greater positive behavioral synchrony was related to greater child self-regulation, regardless of the level of family risk, thereby providing support for hypothesis three. The R^2 change due to the interaction term was .04

Discussion

The development of self-regulation unfolds in the context of the parent-child relationship (Moore & Calkins, 2004; Feldman, 2007b; Posner & Rothbart, 2000); as such, continued attention to relationship features that predict self-regulation is warranted (Fay-Stammbach et al., 2014). Positive behavioral synchrony among parents and children in particular has been linked to the development of self-regulation in preschoolers (e.g., Kochanska et al., 2008; Laible & Thompson, 2000). Bio-behavioral theories of synchrony suggest that behavioral and physiological processes are interdependent (Feldman, 2012); thus, the examination of physiological synchrony is important for advancing conceptual models regarding the role of the parent-child relationship in children's self-regulation development. Findings from this study contribute meaningfully to the extant literature by documenting methods for assessing physiological synchrony among preschoolers and parents and illustrating the complex ways that such synchrony relates to positive behavioral synchrony and child self-regulation in the context of family risk.

Prior work has not examined moment-to-moment physiological synchrony among mother-preschooler dyads. Thus, the first goal of this study was to determine whether we could identify such a process during a lab-based interaction designed to reflect one that might typically occur among parents and children during this developmental period. The assessment of cardiovascular activity, and IBI in particular, allowed us to analyze synchrony at a micro level, thereby capturing moment-to-moment concordance between mother and child physiological activity. Using a statistical approach that accounted for the autocorrelation within each member's IBI series, we found that moment-to-moment physiological synchrony does occur among mother-preschooler dyads. Further, the phenomenon was only present during the interaction task, not the baseline (non-interactive) assessment. This suggests that the findings are not due to the fact that some dyads were simply more physiologically attuned to each other in a passive way, but rather reflect the idea that physiological synchrony, as assessed in this study, is most salient during active interactions.

The next aim of the study was to examine relations between physiological synchrony, child self-regulation, and positive behavioral synchrony in the context of family risk. In partial support of study hypotheses, when family risk was high, positive behavioral synchrony was highest when physiological synchrony was low. Partners who are in sync physiologically with one another under low-risk conditions may find their interactions more pleasant and rewarding, thus increasing their desire to maintain a positive give-and-take with one another. High physiological synchrony in the context of high levels of risk may reflect dysregulated stress responses that interfere with partners' abilities to attend to one another's needs, appropriately negotiate conflicts that arise, or otherwise engage in cooperative behaviors. High physiological synchrony under conditions of risk and negative behavioral interactions are likely to reciprocally influence one another. An unpleasant interaction with a close relationship partner is likely to be stressful, which may, in turn, serve to further increase the experience of negative emotions and magnify physiological synchrony that interferes with positive behavioral interactions. Levenson and Gottman (1983) found that physiological synchrony was highest among distressed marital couples and proposed that the negative emotional experiences that are a hallmark of distressed marriages are associated with greater levels of physiological arousal that, in turn, contribute to greater levels of physiological synchrony. The findings here likewise suggests that physiological synchrony among partners may or may not reflect a harmonious relationship and, in the context of higher levels of family risk, may actually confer additional risk for maladaptation.

Similar patterns of results were found when examining the relation between physiological synchrony and child self-regulation. At high levels of family risk, child self-regulation was greater when physiological synchrony was low than when physiological synchrony was high. In other words, family risk exacerbated poor functioning in the context of high physiological synchrony. In fact, child self-regulation was lowest in the context of high family risk and high physiological synchrony. High physiological synchrony suggests that partners are closely attuned to one another. In the context of high levels of risk though, individuals may experience greater levels of negative emotion and physiological synchrony under such conditions may be undesirable. Physiological synchrony under conditions of high risk may exacerbate already high levels of negative emotional experience, which may become overwhelming to the child and interfere with the ability to self-regulate when needed. A mismatch of physiological states in the context of risk may be adaptive because it may prevent further escalation of negative emotional experience that may otherwise occur. On the one hand, a mismatch among partners under conditions of high risk may signal that one partner is able to buffer the negative effects of family risk by modulating their physiological functioning. On the other hand, physiological synchrony under conditions of low risk may facilitate child self-regulation because such synchrony may reflect a harmonious relationship characterized by moderate levels of emotional arousal that are conducive to the development of self-regulatory skills. In fact, we hypothesized that under conditions of low family risk, physiological synchrony would be associated with higher levels of positive behavioral synchrony and child self-regulation; however, only the conditional effects at high levels of family risk were significant. It is unclear why there were no significant effects at low levels of family risk. It could simply be that family risk is most influential at high levels. Inspection of the graphs; however, suggests that there may be a trend, albeit a non-significant one, such that the highest levels of positive behavioral synchrony and child self-regulation may occur in the context of high physiological synchrony and low levels of family risk. Given the paucity of research examining physiological synchrony in the context of family risk, future research with larger samples is needed to help elucidate the complex relations among these variables.

In contrast, positive behavioral synchrony was positively associated with child self-regulation, regardless of family risk status. Positive behavioral synchrony has been consistently found to be linked to child self-regulation, particularly in early childhood (Feldman et al., 1999; Kochanska et al., 2008). The present results serve to extend this area of research by demonstrating the important role of positive behavioral synchrony in child self-regulation, even in the presence of multiple family risk factors.

Collectively, the novel results of this study help to advance developmental models by demonstrating the presence of moment-to-moment physiological synchrony in mother-preschooler dyads and the ways that this synchrony relates to behavioral indices of parent-child synchrony and child self-regulation in the context of risk. Further, the sample was diverse in terms of both socioeconomic status and race, strengthening the external validity of the study. Despite these major strengths, limitations are noted. Our measure of cumulative family risk was broad by design, which was methodologically appropriate for a community sample; however, we echo others (e.g., Grant, Compas, Stuhlmacher, Thurm, McMahon, & Halpert, 2003; Obradović, Shaffer, & Masten, 2012) in acknowledging that risk indices obscure developmental processes of influence. We measured a specific component of child self-regulation, which, while useful for answering the research questions posed in this study, also provided a narrow focus. Future work should include a broader assessment of child self-regulation across attentional, emotional, and behavioral domains. This study only included mothers; fathers too play a unique role in child development (McElwain, Halbserstadt, & Volling, 2007; Morelen & Suveg, 2012) and should be included in future work. This cross-sectional study documented preliminary relations among variables not previously examined. Longitudinal, observational work that includes dynamic measures of behavioral synchrony (e.g., state-space grids; Hollenstein, 2013) is necessary to study how the interplay of behavioral and physiological processes related to the parent-child relationship influence important child outcomes over time. Behavioral and physiological synchrony are most likely mutually influential, with each partner (both mother and child) impacting the dynamics of the interaction. Though this study contributes to our understanding of physiological synchrony among mother-preschooler dyads in the context of family risk, much work remains to better explicate how physiological synchrony operates at various developmental periods and in different contexts.

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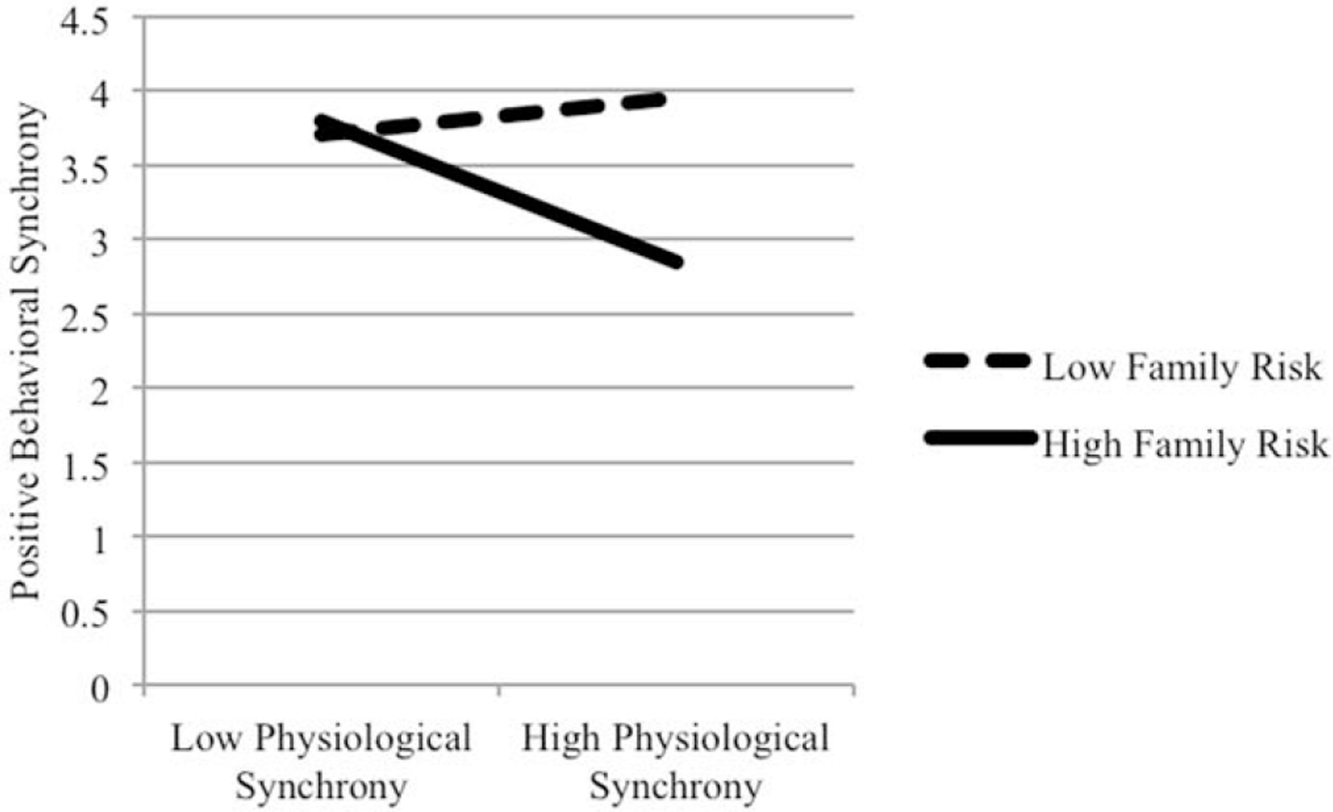

Figure 1.

Families with high levels of risk exhibited higher levels of positive behavioral synchrony when physiological synchrony was low than when it was high.

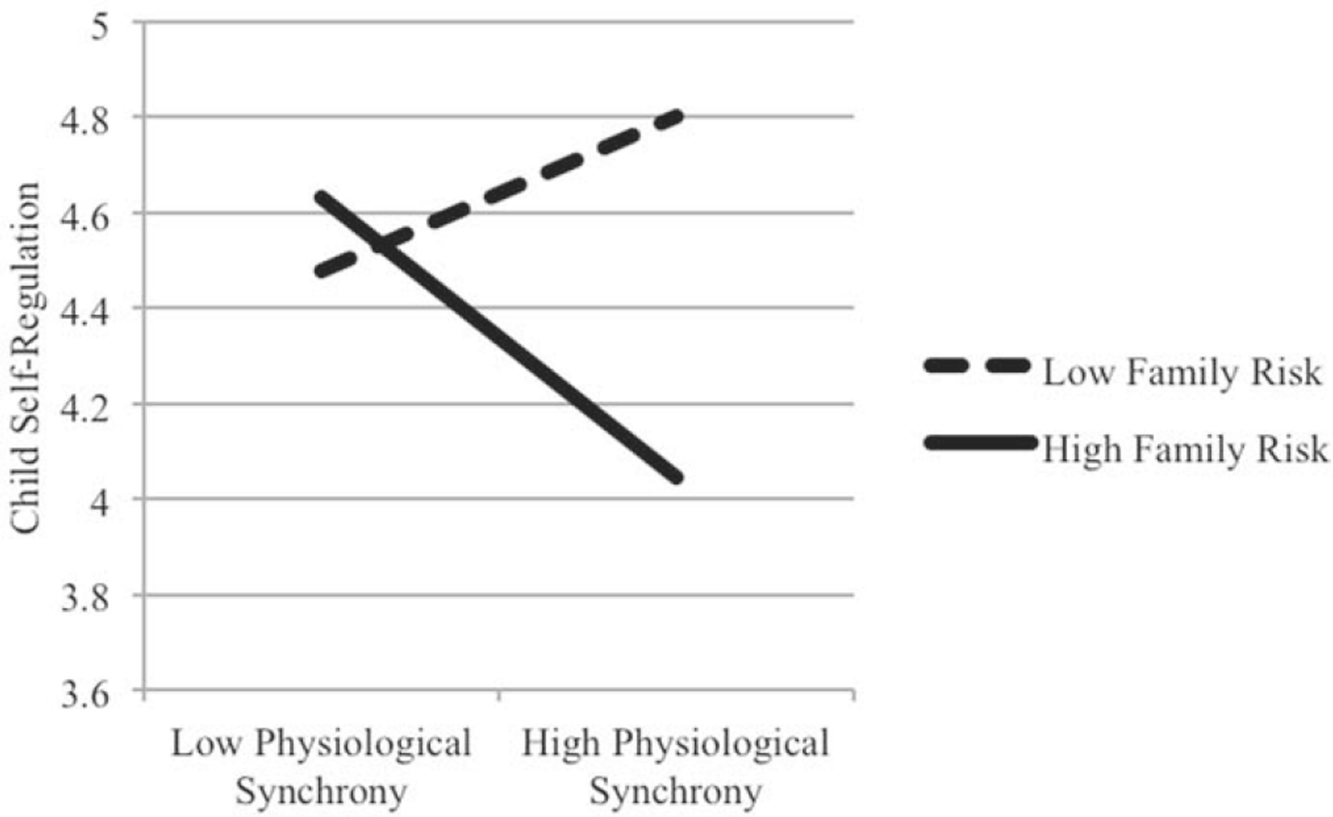

Figure 2.
Children of families with higher levels of risk showed greater self-regulation when physiological synchrony was low than when it was high.

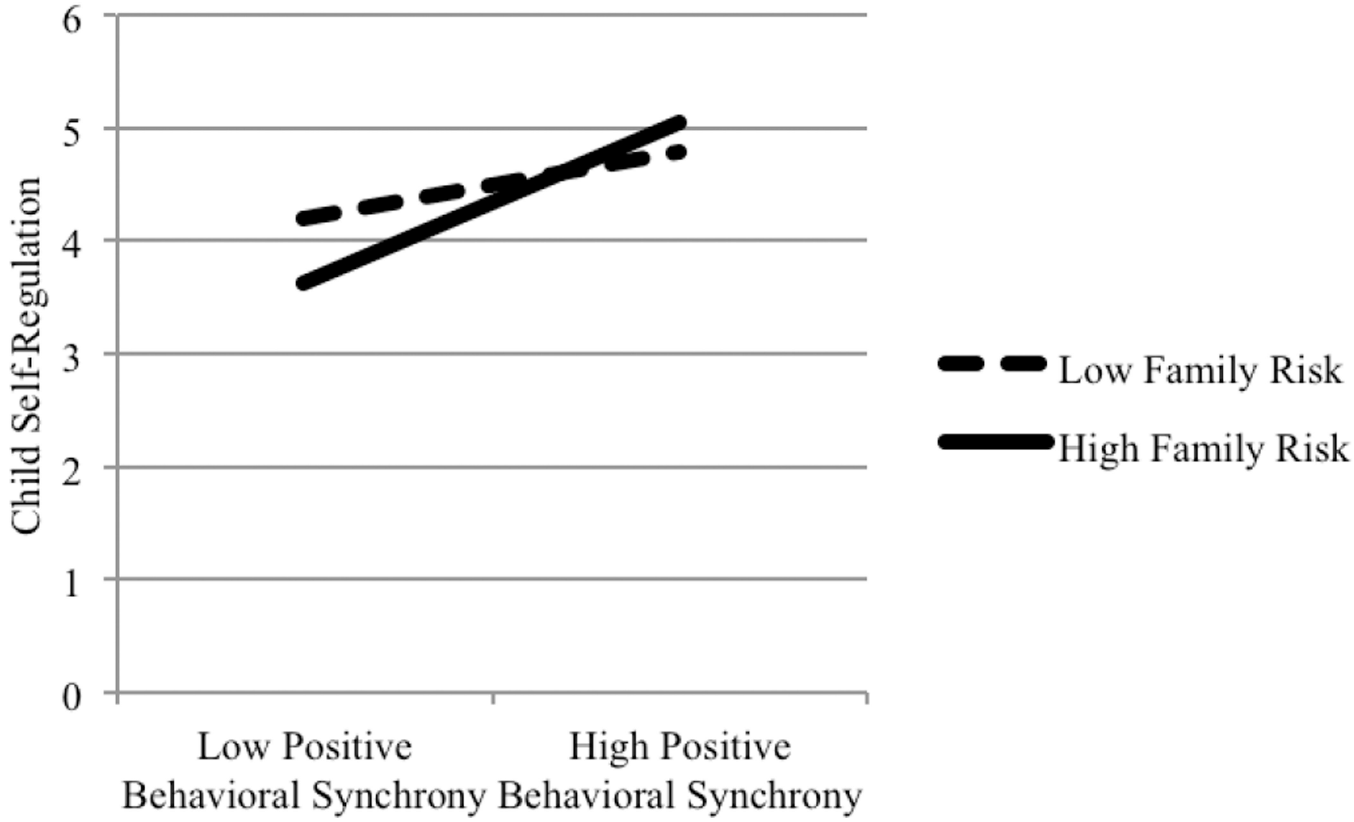

Figure 3.
Positive behavioral synchrony was positively related to child self-regulation, regardless of family risk status.

Table 1

Descriptive Statistics for Mother-Child Physiological Synchrony, Mother-Child Positive Behavioral Synchrony, and Child Self-Regulation According to Risk Status

	Lower-Risk			Higher-Risk		
Variable	**M**	**SD**	**Range**	**M**	**SD**	**Range**
1. Physiological Synchrony	.03	.06	−.15–.19	.003	.07	−.12–.10
2. Behavioral Synchrony	3.85	1.03	1–5	3.19	1.31	1–5
3. Child Self-Regulation	4.60	.65	3–5	4.11	1.15	1–5

** $p < .01$.

* $p < .05$.

Table 2

Intercorrelations Among Mother-Child Physiological Synchrony, Mother-Child Behavioral Synchrony, and Child Self-Regulation According to Risk Status

	Lower-Risk			Higher-Risk		
Variable	**1**	**2**	**3**	**1**	**2**	**3**
1. Physiological Synchrony	—	0.08	0.12	—	−0.40*	−0.25
2. Behavioral Synchrony		—	0.30*		—	0.72**
3. Child Self-Regulation			—			—

** $p < .01$.

* $p < .05$.

Table 3

Family Risk as a Moderator of the Relations Between Physiological Synchrony and Positive Behavioral Synchrony and Child Self-Regulation (N = 71)

Outcome Variable	b (SE)	t	R^2	F (3, 67)	95% CI
Positive Behavioral Synchrony			.13	3.21*	
Physiological Synchrony	−2.54 (1.91)	−1.33			−6.36, 1.28
Family Risk	−.19 (.10)	−1.95			−.39, .005
Physiological Synchrony * Family Risk	−3.33 (1.60)	−2.09*			−6.51, −.15
−1 SD (Family Risk)	1.85 (2.63)	.70			−3.40, 7.10
+1 SD (Family Risk)	−6.92 (3.04)	−2.28*			−12.98, −.86
Child Self-Regulation			.12	2.93*	
Physiological Synchrony	−.96 (1.32)	−.73			−3.58, 1.67
Family Risk	−.11 (.07)	−1.69			−.25, .02
Physiological Synchrony * Family Risk	−2.54 (1.10)	−2.32*			−4.73, −.35
−1 SD (Family Risk)	2.38 (1.81)	1.32			−1.22, 5.99
+1 SD (Family Risk)	−4.30 (2.09)	−2.06*			−8.47, −.13

Note. All regression coefficients are unstandardized

** $p < .01$.

* $p < .05$.

Table 4

Family Risk as a Moderator of the Relation Between Positive Behavioral Synchrony and Child Self-Regulation (N = 93)

Outcome Variable	b (SE)	t	R^2	F (3, 89)	95% CI
Child Self-Regulation			.43	22.22**	
Positive Behavioral Synchrony	.41 (.07)	5.95**			.28, .55
Family Risk	−.06 (.06)	−.94			−.18, .06
Positive Behavioral Synchrony * Family Risk	.13 (.05)	2.61*			.03, .23
−1 SD (Family Risk)	.24 (.11)	2.26*			.03, .46
+1 SD (Family Risk)	.58 (.08)	7.20**			.42, .74

Note. All regression coefficients are unstandardized

** $p < .01$.

* $p < .05$.