Received: 17 March 2021 | Revised: 9 August 2021 | Accepted: 15 August 2021

DOI: 10.1002/dev.22196

RESEARCH ARTICLE

Developmental Psychobiology WILEY

Parent–child physiological synchrony: Concurrent and lagged effects during dyadic laboratory interaction

Emma Armstrong-Carter | Jonas G. Miller | Jelena Obradović

Stanford University, Stanford, California, USA

Correspondence
Emma Armstrong-Carter, Graduate School of Education, Stanford University, 520 Galvez Mall, Stanford, CA 94305, USA.
Email: emmaac@stanford.edu

Funding information
Jacobs Foundation Advanced Research Fellowship, Grant/Award Number: 2017-1261-07; Institute of Education Sciences, U.S. Department of Education, Grant/Award Number: R305B140009; Stanford Data Science Fellowship.

Abstract

This study investigated whether parents and kindergarten children show concurrent and time-lagged physiological synchrony during dyadic interaction. Further, we tested whether parent–child behavioral co-regulation was associated with concurrent and time-lagged synchrony, and whether synchrony varied by the type of interaction task. Participants were 94 children (M_{age} = 5.6 years, 56% female) and their parents. We simultaneously measured parent and child respiratory sinus arrhythmia (RSA) during four dyadic interaction tasks: free play, clean up, problem-solving, and puzzle teaching. We found that synchrony varied by task. Concurrent synchrony occurred only during the puzzle teaching task, such that parent and child RSA were significantly and positively associated with each other simultaneously. Time-lagged synchrony occurred only during the problem-solving task, such that parent RSA was positively associated with child RSA 30 seconds later, and child RSA was negatively associated with parent RSA 30 seconds later. Although behavioral co-regulation and physiological synchrony have been conceptualized as markers of responsive parent–child interactions, our study finds no evidence that physiological synchrony is associated with between-dyad differences in behavioral co-regulation.

KEYWORDS
kindergarten, parent–child relationship, stress-physiology, synchrony

1 | INTRODUCTION

Positive parent–child relationships that are grounded in mutual responsivity help children to internalize self-regulated behavior and adjust positively across developmental domains (MacPhee, Lunkenheimer, & Riggs, 2015). The responsivity of parent–child relationships can be reflected in their *physiological synchrony*, the extent to which parent and child display covarying physiological responses over the course of dyadic interaction (Davis, West, Bilms, Morelen, & Suveg, 2018). However, prior research on physiological synchrony has largely focused on samples of infants, preschoolers, and adolescents. Researchers know less about physiological synchrony in 5-year-old children, who rely closely on their parents, but also independently face new daily challenges in kindergarten that require internalized self-regulated behavior (Calkins, 2011). This study used hierarchical linear modeling to investigate whether parents and kindergartners show concurrent and time-lagged physiological synchrony over the course of dyadic interaction. Further, we examined whether concurrent and time-lagged synchrony varied by the type of dyadic interaction task. Finally, we tested whether concurrent and time-lagged synchrony were associated with levels of parent–child behavioral co-regulation, that is, the extent to which the parent and child displayed positive, reciprocal, and supportive patterns of behavior (Bardack et al., 2019).

1.1 | Parent–child physiological synchrony and the parasympathetic nervous system

As children and parents interact, their bodies respond to each other physiologically. Physiology is a time-varying measure that can be calculated continuously. Measuring child and parent physiology continuously and simultaneously reveals variability in the extent to which their physiological responses dynamically covary or *synchronize* during dyadic interaction (Davis et al., 2018). In other words, physiological synchrony is the extent to which increases or decreases in the child's physiological activation correspond to changes in the parent's physiological activation, and vice versa.

According to the biobehavioral conceptual framework of attachment, parent–child physiological synchrony is a uniquely formative experience for children's neurological, social, and emotional development (Feldman et al., 2017). Specifically, physiological synchrony is believed to influence children's brain maturation and ability to form interpersonal attachments, self-regulate, and engage positively with their environment (Feldman et al., 2017). Although theoretical models of synchrony were initially developed using research from infants and their parents, synchrony is believed to influence children's adaptation from infancy through adolescence (Feldman et al., 2017). However, prior emperical research has focused on infancy, preschool-age, and adolescence, and researchers know less about physiological synchrony in 5-year-old children and their parents. It is important to extend the study of parent–child synchrony to the kindergarten period, which marks an important developmental transition when children are increasingly expected to independently regulate their arousal, emotions, and behavior in educational settings, while still relying on their parents for co-regulation.

Physiological synchrony can be measured using a variety of physiological indices such as hormone levels (e.g., cortisol) and cardiac measures (e.g., heart rate). We focus here on synchrony of the parasympathetic nervous system. The parasympathetic nervous system offers unique insight as a marker of physiological synchrony, because it responds dynamically to mild and moderate social and emotional experiences from moment to moment (Porges, 2007). The parasympathetic nervous system is measured via respiratory sinus arrhythmia (RSA), reflecting the high-frequency heart rate variation controlled by efferent fibers of the vagus nerve during the respiratory cycle. Polyvagal theory posits that RSA reflects positive coping and engagement with contextual stimuli or challenges in the moment (Porges, 2007). Therefore, changes in parent and child RSA may help illuminate the degree to which parent and child are mutually responsive to each other during dyadic interaction.

Using repeated measurements, RSA can be calculated repeatedly across short periods of time or "epochs," which traditionally last 30 s (Davis et al., 2017). Fluctuations in parent and child RSA can then be analyzed on multiple time frames (Obradović & Boyce, 2012). For example, researchers can examine *concurrent synchrony* by testing whether parent and child physiological activation both increase or decrease simultaneously, within each epoch of time (e.g., Li, Sturge-Apple, Liu, & Davies, 2020). In addition, researchers can examine *time-lagged synchrony* by testing whether increases or decreases in the physiological activation of one partner correspond with changes in the physiological activation of the other in a "subsequent" epoch (e.g., Helm, Miller, Kahle, Troxel, & Hastings, 2018). Although both concurrent and time-lagged models reflect dynamic physiological synchrony between dyadic partners, each model offers unique insight.

1.2 | Concurrent versus time-lagged physiological synchrony

First, concurrent models indicate the extent to which parent and child physiological changes co-occur simultaneously. As such, concurrent parent–child synchrony is the correlation between simultaneous changes in parent and child RSA, and is understood as the extent to which parent and child are attuned to each other in the moment (Feldman et al., 2017). In contrast, investigating *time-lagged* synchrony sheds light on potential directionality, that is, the extent to which the parent may influence the child or vice versa (Helm et al., 2018). Time-lagged models illustrate not just that synchrony occurs, but "how" it emerges. For instance, if only parent physiology predicts subsequent child physiology (but child physiology does not predict parent physiology), then this would suggest that child physiological changes are sensitive and attuned to prior parent physiological changes. If changes in parent physiology predict subsequent changes in child physiology "and" vice versa, this would suggest that parent and child physiology are reciprocally related, potentially indicating that parents and children adjust their physiological arousal in response to their partner's prior physiological state. In this way, investigating time-lagged synchrony can elucidate whether physiological synchrony is driven initially by changes in parent or child physiology.

Initial research on parasympathetic nervous systems (PNS) synchrony focused on *concurrent* synchrony mostly between infants and mothers (e.g., Feldman, 2006; Moore, 2009). This work demonstrated that fluctuations in parent and infant RSA were concurrently associated with each other over the course of interaction tasks, using within-dyad analyses (Ostlund, Measelle, Laurent, Conradt, & Ablow, 2017; Pratt, Singer, Kanat-Maymon, & Feldman, 2015). More recent studies with preschool-age children and adolescents have shown mixed results. On the one hand, a sample of 47 preschoolers found that fluctuations in parent and child RSA were concurrently, positively associated with each other during a free play, clean up, and teaching task (Lunkenheimer et al., 2015; Lunkenheimer, Tiberio, Skoranski, Buss, & Cole, 2018). This finding was replicated in two studies of parents and adolescents engaged in problem-solving discussion tasks (Li et al., 2020; McKillop & Connell, 2018). On the other hand, a study of 83 preschoolers found that parent and child RSA were not concurrently associated with each other during reading and puzzle tasks (Helm et al., 2018). Further, among 10-year-olds from low-socioeconomic status backgrounds, parent and child RSA were only significantly concurrently associated with each other for parents and children with low levels of internalizing symptoms, during a baseline or conflict discussion (Suveg et al., 2019).

Only a few studies have investigated time-lagged synchrony of RSA. One study of 83 preschoolers showed parent RSA positively predicted subsequent child RSA 30 s later, but child RSA was not related to subsequent parent RSA (Helm et al., 2018). This finding was replicated in a sample of 59 adolescents using 15-s time lags (McKillop & Connell, 2018). However, there may be developmental differences in the extent to which parent and child physiology are related. To shed light on developmental change, it is important to investigate whether parents and children show concurrent and time-lagged physiological synchrony at kindergarten age. On the one hand, parent physiology may influence child physiology during kindergarten, or dyads may demonstrate concurrent synchrony, given that kindergarteners are still closely attuned to and reliant on their parents. On the other hand, children's physiology may not be synchronized or may be less synchronized with their parents' physiology during kindergarten (when compared to prior studies of preschool age), given that kindergartners transition toward increasing behavioral independence.

1.3 | Variation in synchrony by task

Given that physiological synchrony is believed to partially reflect the extent to which parents and children are engaged in temporally matched, reciprocal patterns of behavioral and emotional attunement (Feldman et al., 2017), physiological synchrony may be strongest when parents and children are engaged in tasks that are relatively more structured, and require more joint attention and engagement. To empirically demonstrate the contexts in which physiological synchrony occurs, researchers can measure physiological synchrony across several different types of interactions. At age 15, adolescents and parents showed concurrent RSA synchrony during a discussion of pleasant events, but not during a conflict discussion (Amole, Cyranowski, Wright, & Swartz, 2017). In contrast, at age 10, concurrent RSA synchrony was strongest during a conflict discussion, compared to a baseline sitting task and a task in which the child performed a stressful speech while the parent observed (Suveg et al., 2019). At preschool age, concurrent *heart rate* synchrony occurred during a collaborative drawing task, but not during a 4-min baseline period during which mothers and children sat next to each other (Suveg, Shaffer, & Davis, 2016). In another study of preschoolers, concurrent RSA synchrony was strongest during free play and clean up, compared to a structured teaching task (Lunkenheimer et al., 2018). These studies suggest that RSA synchrony varies across different types of interaction and different tasks should be examined separately. This approach may reveal the social contexts in which RSA synchrony occurs or is strongest, and thereby shed light on the environmental circumstances in which RSA synchrony emerges. At kindergarten age, physiological synchrony may occur during tasks that are relatively more structured, but not during tasks that are less structured, because children are learning to independently engage with their environment from their early experiences in the classroom away from their parent.

1.4 | Behavioral correlates of physiological synchrony

Identifying behavioral factors that explain variability in the degree to which dyads display physiological synchrony can help researchers to understand the significance of physiological synchrony for child development. Initial biobehavioral frameworks conceptualized parent–child physiological synchrony as positive (Feldman et al., 2006), but empirical research has shown mixed results as to whether synchrony is associated with parent and child risk factors (e.g., emotional and behavioral challenges). For instance, one study suggested that parent–child physiological synchrony is strongest among dyads who exhibit insecure-resistant attachment style (Smith et al., 2016), whereas another study suggested that parent–child physiological synchrony is strongest among dyads who experience more optimal emotional and behavioral adjustment (i.e., fewer internalizing symptoms and aggressive behaviors; Lunkenheimer et al., 2017). Further, the association between parents' and children's behavioral adaptation and their physiological synchrony likely depends on the study context, measures, and developmental timing (Davis et al., 2018). More research that investigates how parent and child behavior are related to physiological synchrony at kindergarten age may help to clarify the implications of physiological synchrony during this period.

In particular, researchers have hypothesized that parent–child physiological synchrony may be based, in part, on the quality of the parent–child interaction, also known as parent–child positive behavioral co-regulation (Davis et al., 2018). Positive behavioral co-regulation reflects the extent to which parent and child display positive, reciprocal, and harmonious patterns of behavior during shared dyadic interactions, and is uniquely important for child adjustment (MacPhee et al., 2015). Young children from dyads that show more positive behavioral co-regulation exhibit more self-regulated behavior (Bardack, Herbers, & Obradović, 2017; Lunkenheimer, Hamby, Lobo, Cole, & Olson, 2020; Scholtes, Lyons, & Skowron, 2021; Suveg et al., 2016), and respond with greater RSA withdrawal during individualized laboratory challenges (Armstrong-Carter, Sulik, & Obradović, 2021). However, it remains unclear whether positive behavioral co-regulation is related to parent–child physiological synchrony.

If they are related, then physiological synchrony may be useful as a marker of effectiveness for interventions designed to improve the quality of parent–child relationships (e.g., Granic, O'Hara, Pepler, & Lewis, 2007).

In order to understand the behavioral correlates of physiological synchrony, researchers should first establish whether there is meaningful variability in the degree to which dyads display physiological synchrony. Several studies have investigated the behavioral correlates of concurrent RSA synchrony, demonstrating that broad measures of parenting quality (e.g., maternal engagement) are positively linked to physiological synchrony from preschool age to adolescence (Lunkenheimer, Kemp, Lucas-Thompson, Cole, & Albrecht, 2017; McKillop & Connell, 2018; Suveg et al., 2019; Woody, Feurer, Sosoo, Hastings, & Gibb, 2016). Some prior studies did not report whether there was significant between-dyad variability in physiological synchrony (Lunkenheimer et al., 2015; McKillop & Connell, 2018; Suveg et al., 2019, 2016; Woody et al., 2016), whereas others found evidence of significant between-dyad variability in physiological synchrony at preschool age and in adolescence (Amole et al., 2017; Helm et al., 2018; Li et al., 2020). This work illustrated that on average, parents and adolescents with higher levels of emotional well-being showed stronger, more positive concurrent RSA synchrony (Amole et al., 2017; Li et al., 2020). Moreover, parents and preschoolers with higher levels of positive maternal teaching behaviors show stronger, more positive concurrent RSA synchrony, whereas dyads who experience maternal disengagement show weaker concurrent RSA synchrony (Skoranski, Lunkenheimer, & Lucas-Thompson, 2017). More research that investigates whether there is significant variability in the degree of synchrony between dyads can help researchers to understand whether individual differences in dyadic behavior may be related to shared patterns of physiological arousal.

1.5 | Current study

This study investigated synchrony of parent and child PNS. We examined whether (1) parents and children showed concurrent and time-lagged PNS synchrony; (2) these two types of synchrony varied by the context of the interaction task; and (3) positive behavioral co-regulation was associated with concurrent and time-lagged synchrony or the average-level correlation between parent and child physiology. We measured parent and child RSA during 20 min of varied dyadic interaction, including free play, clean up, problem-solving, and teaching tasks. We used hierarchical linear models and controlled for average levels of RSA. This approach enabled us to disaggregate dynamic RSA synchrony from the average-level correlation between parent and child mean RSA, which might be partially influenced by shared biology or environmental experiences (Davis et al., 2018). To capture positive parent–child co-regulation, we used a second-by-second independent coding of child and parent behavioral states during interaction (Bardack et al., 2017).

We hypothesized that: (1) Fluctuations in parent and child RSA would be significantly and positively associated with each other over the course of dyadic interaction in both concurrent and time-lagged models, which would reveal bidirectional associations. We hypothesized a positive direction because the majority of past research has found either positive synchrony or no significant synchrony (for a review, see Davis et al., 2018), whereas only one study found negative synchrony throughout the study (Ostlund et al., 2017). In another study, synchrony ranged from moderately negative to moderately positive, but the majority of 43 dyads show positive synchrony (Creavy, Gatzke-Kopp, Zhang, Fishbein, & Kiser, 2020). (2) Synchrony would differ across tasks, such that synchrony would be stronger in the more structured tasks (i.e., teaching and problem-solving tasks) compared to the less structured tasks (i.e., free play and clean up). (3) Higher levels of positive parent–child behavioral co-regulation would be associated with stronger concurrent and time-lagged synchrony, and the association between parent and child average RSA would be stronger for dyads who display high levels of positive parent–child behavioral co-regulation. This hypothesis was informed by biobehavioral perspectives on parent–child physiological synchrony (Feldman et al., 2006), although empirical evidence supporting this hypothesis has been mixed.

2 | METHOD

2.1 | Participants

The participants were 94 kindergarteners (M_{age} = 5.62 years; *SD* = 0.55; 52% female [*n* = 49]) drawn from a sample of 102 children who participated in a laboratory study with a primary caregiver (M_{age} = 38.92 years; *SD* = 6.82 years; 93% female [*n* = 87]). Eight children and their caregivers were excluded from the current study because they did not complete the dyadic physiological protocol. Two additional parents were missing physiological data. Families were recruited with advertisements at community centers, preschools, elementary schools, and libraries and were eligible if they had a child who was fluent in English and entering kindergarten or first grade. The sample was racially diverse, with caregivers reporting the children as 36% White, 26% Hispanic/Latino, 20% Asian, 4% Black, and 14% Multiracial/Other. Seventeen percent of participating caregivers were single parents. Seventeen percent reported educational attainment of a high school diploma or less, whereas 42% had earned a graduate or professional degree. Consistent with this, 23% of the families reported household income less than $50,000, whereas 36% reported household income greater than $200,000.

2.2 | Procedure

Primary caregivers and children visited a university research laboratory to complete a 3-h protocol. Upon arrival, research assistants greeted and consented the dyad, introduced them to the laboratory setting and the study protocol, and set up equipment for measuring physiological responses. Parents completed an in-person survey, which included demographic information, with a trained interviewer. During the 2.5-h session, children completed a series of challenge tasks designed to elicit physiological response with a research assistant; these are not used in the current study. Toward the end of the session, parents and children reunited to participate in four video-recorded, structured tasks designed to capture the quality of the parent–child interaction and, specifically, patterns of parent–child behavioral co-regulation. The parent–child interaction protocol lasted for approximately 30 min (including transition time between tasks) and was video-recorded. During the free play task, the parent and child were asked to play together with provided toys; unbeknownst to the child, the parent had been instructed to enforce a rule disallowing the child from touching certain attractive toys. During the clean-up task, the parent was instructed to read a magazine while asking the child to clean up the toys, but was not prohibited explicitly from helping the child during this task. During the problem-solving discussion, the dyad was asked to try to resolve a salient issue that the parent had chosen from a list of age-appropriate, parent–child challenges (e.g., waking up on time, getting along with siblings). During the teaching task, the parent was asked to teach and support the child in completing a series of challenging geometric puzzles called the "Tangos Game." The free play, problem-solving, and teaching tasks each lasted approximately 5–6 min. The clean-up task lasted approximately 3 min. All procedures were approved by the Stanford University Institutional Review Board.

2.3 | Measures

2.3.1 | Physiological response

During the parent–child interaction tasks, parent and child RSA response was measured using a Wireless BioNomadix RSP module (BIOPAC Systems, Goleta, CA). This was a small electrocardiogram device attached separately to parent and child. From this device, we derived parent and child RSA. RSA was estimated as the natural logarithm of the variance of heart period within the high-frequency bandpass associated with respiration. The high-frequency bandpass was set to 0.15–0.80 Hz for estimating child RSA (Bar-Haim, Marshall, & Fox, 2000; Rudolph, Rudolph, Hostetter, Lister, & Siegel, 2003) and 0.12–0.40 Hz for estimating parent RSA (Bar-Haim et al., 2000; Rudolph et al., 2003). Prior to analyses, each waveform was verified, interbeat intervals were checked visually, and artifacts were removed. Specifically, research assistants underwent a rigorous training process for processing the ECG data and calculating RSA values using AcqKnowledge software. All research assistants coded 10% of the same files, and demonstrated good reliability (ICC > .95). RSA values were then calculated in 30-s epochs.

For each parent and child, we calculated two RSA variables. First, for each individual (i.e., parent or child) we calculated their average RSA value across all of their epochs for a given task (e.g., full interaction, free play, clean up, problem-solving, or teaching task). Second, we mean-centered each RSA value in each epoch around that individual's person-mean for a given task. These mean-centered RSA variables varied across epochs.

2.3.2 | Positive parent–child behavioral co-regulation

To measure parent–child positive co-regulation, we used an innovative state-space grid (SSG) methodology, which captures observer ratings of moment-to-moment changes in dyadic behavior patterns. Using a 4 × 4 SSG grid, parent and child behaviors were coded on a continuous, second-by-second basis into mutually exclusive and exhaustive categories reflecting the behavioral state of the dyad (see Bardack, Herbers, & Obradović, 2017). Child behavior was plotted on the *y*-axis and was coded as: (1) active on task (e.g., leading play, engaging the parent in joint attention); (2) passive on task (e.g., following parent's lead during play, listening to parent); (3) withdrawn/disengaged (e.g., avoiding eye contact, turning away); or (4) defiant/dysregulated (e.g., verbally refusing; expressing emotional distress). Parent behavior was plotted on the *x*-axis and was coded as: (1) positive control (e.g., redirecting child's attention to on-task behavior, comforting); (2) following the child's lead (e.g., responding to child's play and verbalizations); (3) disengaged (e.g., ignoring child, appearing distracted or withdrawn); or (4) negative control (e.g., criticizing or showing harsh physical contact). We defined positive co-regulation as temporally co-occurring parent–child behaviors in which the parent guides or maintains children's well-regulated attention and behavior. In other words, the cells selected from the grid represented parent positive control behaviors when the child was showing either positive behaviors (i.e., actively and passively on-task) or negative behaviors (i.e., withdrawn from the interaction or exhibiting defiant, dysregulated behavior).

Using Gridware 1.5 (Lamey, Hollenstein, Lewis, & Granic, 2004), we derived variables characterizing the tendency of dyadic behavior to occur and maintain within the region of parent–child positive co-regulation: (a) the proportion of time spent in this region relative to the whole grid ($M = 0.82$, $SD = 0.09$), (b) average duration (in seconds) per cell ($M = 150.54$, $SD = 23.46$) in this region, and (c) average return time (reversed; $M = 2.80$, $SD = 0.67$) to this region. We standardized and averaged these three variables to create a composite score for parent–child positive co-regulation ($\alpha = .87$). For each dyad, we calculated five *positive parent–child behavioral co-regulation* values: across the course of the full interaction, free play, clean up, problem-solving, and teaching task.

2.3.3 | Child and family demographics

Child gender was coded 0 = Boys, 1 = Girls. *Child age* was entered as numerical age. *Family socioeconomic status* (SES) was a composite of family income and maternal education.

2.4 | Missing data and outliers

All available data were used in the analysis. All children in the analytic sample ($N = 94$) had complete demographic and positive parent–child behavioral co-regulation data. On average, children and parents had 29 epochs of usable RSA data across the full interaction ($SD = 11.50$, Min = 0, Max = 43). Most dyads had nine epochs during the free play (89% of dyads), problem-solving (95%), and teaching tasks (93%), and five epochs during the clean-up task (94%). All outliers >3*SD* were winsorized to 3*SD* ($N = 35$ epochs for parent RSA, $N = 6$ epochs for child RSA). In our analytical sample, missing RSA data were due to technical issues such as poor signal quality from the electrocardiogram, and noisy data due to physical movements (e.g., sneezing, coughing, or excessive body movements).

2.5 | Statistical analysis

We used hierarchical linear models that nested epochs (Level 1) within dyads (Level 2). Following recent expert recommendations, we person-centered all Level 1 RSA values, and controlled for person-average values for RSA (Davis et al., 2018; Helm et al., 2018). This statistical approach helps to isolate within-dyad versus between-dyad effects (Curran & Bauer, 2011; Wang & Maxwell, 2015), and therefore is well-suited to the temporal and dyadic nature of our data. Given that our primary predictors were mean-centered and not standardized, we report unstandardized beta estimates that cannot be interpreted as effect sizes.

Our first research question was whether parents and children showed concurrent and time-lagged PNS synchrony. For *concurrent* synchrony, we tested person-centered child RSA as a function of person-centered parent RSA in the same epoch and person-average parent RSA across epochs (Model 1). We tested this first during the entire dyadic interaction (i.e., across all four tasks) and then separately within each task (free play, clean up, problem-solving, and teaching). For separate analyses within each task, the average RSA control variables were derived within that task only. Specifically, we used the equations below, in which$pRSA_{i,e}$ and $cRSA_{i,e}$ denote the i individual parent and child mean-centered RSA values, respectively, during the t task during epoch e. In models where we tested the full dyadic interaction across all four tasks, t reflects all four tasks. μ denotes an individual's person-mean value of RSA within a given task or across the full interaction, depending on the model. ε denotes the error term.

$$cRSA_{i,e} = \beta_0 + \mu P_i + \beta pRSA_{i,e} + \varepsilon C_{i,e}. \quad (1)$$

For *time-lagged* synchrony, we first tested whether parent RSA in a given epoch predicted child RSA in the next epoch (i.e., 30 s later), again controlling for parent average RSA values (Model 2):

$$pRSA_{i,e+1} = \beta_0 + \mu C_i + \beta cRSA_{i,e} + \varepsilon P_{i,e}. \quad (2)$$

Conversely, in a separate model, we then tested whether child RSA in a given epoch predicted parent RSA in the next epoch (i.e., 30 s later), again controlling for child average RSA levels (Model 3):

$$cRSA_{i,e+1} = \beta_0 + \mu P_i + \beta pRSA_{i,e} + \varepsilon C_{i,e}. \quad (3)$$

We did not test time-lagged models across the full interaction due to temporal breaks of a few minutes between each task. As a follow-up to the time-lagged analysis, we additionally tested whether parent RSA predicted subsequent child RSA "over and above" concurrent child RSA, and vice versa. This approach increased the robustness of our findings and provided greater insight into the potential directionality of the associations. Specifically, within each task, we first tested whether parent RSA in a given epoch predicted child RSA in the next epoch (i.e., 30 s later), controlling for parent average RSA values "and" child RSA in the "same" epoch. Conversely, in a separate model, we next tested whether child RSA in a given epoch predicted parent RSA in the next epoch (i.e., 30 s later), again controlling for child average RSA levels "and" parent RSA in the "same" epoch:

$$pRSA_{i,e+1} = \beta_0 + \mu C_i + \beta cRSA_{i,e} + \beta pRSA_{i,e} + \varepsilon P_{i,e}, \quad (4)$$

$$cRSA_{i,e+1} = \beta_0 + \mu P_i + \beta pRSA_{i,e} + \beta cRSA_{i,e} + \varepsilon C_{i,e}. \quad (5)$$

Our second research question was whether synchrony varied by the type of interaction task. We addressed this by examining synchrony model (described above), first across the full interaction, then separately within each interaction task.

Our third research question was whether positive behavioral co-regulation was associated with concurrent and time-lagged synchrony between- and within-dyads. As a prerequisite to determine whether it was appropriate to test positive parent–child behavioral co-regulation as a predictor of synchrony, we tested the same models as above (concurrent and time-lagged), but included random slopes on the intercept and the mean-centered predictor variable to establish whether synchrony varied significantly between dyads. u denotes random effects applied to the intercept (0) or variable slopes:

$$cRSA_{i,e} = \beta_0 + \mu P_i + \beta pRSA_{i,e} + u0 + upRSA_{i,e} + \varepsilon C_{i,e}, \quad (6)$$

$$pRSA_{i,e+1} = \beta_0 + \mu C_i + \beta cRSA_{i,e} + u0 + u\underline{c}RSA_{i,e} + \varepsilon P_{i,e}, \quad (7)$$

$$cRSA_{i,e+1} = \beta_0 + \mu P_i + \beta pRSA_{i,e} + u0 + upRSA_{i,e} + \varepsilon C_{i,e}. \quad (8)$$

We then compared the statistical fit between the two equivalent models with and without random slopes using "pchisq" function in R. We then added two interaction terms as simultaneous predictors. Specifically, we created one cross-level interaction term (i.e., positive parent–child behavioral co-regulation on Level 2 multiplied by mean-centered parent RSA on Level 1), and one Level 2 interaction term (i.e., positive parent–child behavioral co-regulation on Level 2 multiplied by person-average parent RSA on Level 2). We included both of these interaction terms as predictors of child RSA in the model. We tested this model first across the full interaction, then separately within each interaction task.

All analyses were conducted using R. Child gender, age, and family socioeconomic status were not correlated significantly with parent or child RSA ($ps > .05$), so they were not included as covariates.

3 | RESULTS

Table 1 displays descriptive statistics for parent and child RSA by task. Table 2 displays descriptive statistics and bivariate correlations for study constructs, using levels of RSA and parent–child co-regulation averaged across the entire interaction. Average child RSA was correlated positively with average parent RSA ($r = .28$, $p < .01$). Positive parent–child coregulation was correlated positively with family socioeconomic status ($r = .27$, $p < .01$). There were no other significant correlations between study variables.

3.1 | Concurrent RSA synchrony

Table 3 displays the results of the hierarchical linear models. Model 1 represents *concurrent* synchrony in parent and child RSA, over and above the average correlation in parent and child RSA. Across the

TABLE 1 Descriptive statistics for parent and child RSA by task

	1	2	3	4	5	6	7	8
1. P- RSA free play	–							
2. P- RSA clean up	**.87*****	–						
3. P- RSA problem-solving	**.90*****	**.90*****	–					
4. P- RSA teaching	**.91*****	**.86*****	**.92*****	–				
5. C- RSA free play	**.28****	.16	**.26***	**.23***	–			
6. C- RSA clean up	.16	.08	.07	.08	**.80*****	–		
7. C- RSA problem-solving	**.22***	.10	.18+	.19+	**.81*****	**.79*****	–	
8. C- RSA teaching	**.27***	.20+	**.25***	**.26***	**.84*****	**.81*****	**.87*****	–
Mean	5.96	5.91	6.05	5.90	7.14	6.93	7.31	7.30
SD	0.95	1.00	1.04	1.00	0.94	0.97	0.98	0.97
Min	3.28	3.37	2.82	3.29	5.12	4.86	5.37	5.40
Max	9.26	9.38	9.38	9.34	9.12	9.17	9.48	9.50

Note: Significant associations $p < .05$ are bolded. RSA and positive parent–child behavioral co-regulation are average values from across each task. "P-" represents Parent values. "C-" represents Child values.
***$p < .001$;
**$p < .01$;
*$p < .05$.

TABLE 2 Correlations and descriptive statistics for study constructs

	1	2	3	4	5	6
1. Child average RSA	–					
2. Parent average RSA	**.28****	–				
3. Positive parent–child behavioral co-regulation	.05	–.09	–			
4. Girl child	–.07	.08	.02	–		
5. Child age	.15	–.10	.12	–.08	–	
6. Family SES	.04	.02	**.27****	.00	.08	–
Mean	7.22	6.01	0.00	1.53	5.60	–0.02
SD	0.89	1.01	1.00	0.50	0.56	1.01
Min	5.38	3.14	–3.98	1.00	4.42	–2.58
Max	9.39	9.35	1.63	2.00	6.87	1.42

Note: Significant associations $p < .05$ are bolded. RSA and positive parent–child behavioral co-regulation are average values from across the entire dyadic interaction.
***$p < .001$;
**$p < .01$;
*$p < .05$.

entire interaction (i.e., all four tasks), we found *concurrent* synchrony, such that parent and child RSA were significantly and positively associated with each other ($b = 0.05$, $SE = 0.02$, $p = .02$). When we separated out each task, this positive association was significant only during the teaching task ($b = 0.09$, $SE = 0.03$, $p = .01$). Specifically, fluctuations in parent RSA co-occurred with fluctuations in child RSA in the same direction. We found no evidence of concurrent synchrony during free play, clean up, or problem-solving tasks (*bs* = 0.00–0.06, *ps* = .19–.98).

3.2 | Time-lagged RSA synchrony

Table 3 also displays results of *time-lagged* synchrony run separately by task, with Model 2 representing parent-to-child effects, and Model 3 representing child-to-parent effects. In both Model 2 and Model 3, we found time-lagged synchrony during the problem-solving task only, such that parent RSA *positively* predicted subsequent child RSA in Model 2 ($b = 0.10$, $SE = 0.04$, $p = .02$), and child RSA *negatively* predicted subsequent parent RSA in Model 3 with slightly less magnitude ($b = -0.09$, $SE = 0.03$, $p = .01$). We found no evidence of time-lagged synchrony in the free play, clean up, or teaching tasks (*bs* = –.10 to .09, *ps* = .14–.80).

To increase the robustness of our findings, we also tested whether parent RSA continues to predict subsequent child RSA *over and above* concurrent child RSA and vice versa, by additionally controlling for prior epoch levels of each RSA outcome. Again, we found time-lagged synchrony during the problem-solving task only, such that child RSA

TABLE 3 Hierarchical linear model nesting epochs within participants, demonstrating within-dyad and between-dyad associations between parent and child RSA

	Full interaction			Free play			Clean up			Problem-solving			Teaching		
	b	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*	*b*	*SE*	*p*
Model 1: Concurrent dynamic associations: Parent RSA predicting concurrent child RSA															
Intercept	−1.24	0.56	0.03	−1.77	0.63	0.01	−0.77	0.76	0.31	−0.74	0.64	0.25	−0.90	0.59	0.13
Same epoch parent RSA	**0.05**	**0.02**	**0.02**	0.00	0.04	0.98	0.02	0.08	0.81	0.06	0.05	0.19	**0.09**	**0.03**	**0.01**
average Parent RSA	**0.21**	**0.09**	**0.03**	**0.29**	**0.10**	**0.01**	0.09	0.13	0.49	0.14	0.10	0.18	0.17	0.10	0.09
Model 2: Lagged dynamic associations: Parent RSA predicting child subsequent RSA															
Intercept	–	–	–	−1.07	0.60	0.08	−1.50	0.78	0.06	−0.50	0.63	0.42	−1.70	0.59	0.00
Previous epoch parent RSA	–	–	–	0.05	0.04	0.20	−0.10	0.08	0.21	**0.10**	**0.04**	**0.02**	−0.05	0.03	0.18
Average parent RSA	–	–	–	0.17	0.10	0.09	0.20	0.13	0.13	0.11	0.10	0.30	0.31	0.10	0.00
Model 3: Lagged dynamic associations: Child RSA predicting parent subsequent RSA															
Intercept	–	–	–	−1.93	0.80	0.02	−0.38	0.90	0.67	−2.38	0.86	0.01	−1.79	0.87	0.04
Previous epoch child RSA	–	–	–	0.05	0.04	0.17	0.09	0.05	0.07	**−0.09**	**0.03**	**0.01**	0.06	0.05	0.20
Average child RSA	–	–	–	0.26	0.11	0.02	0.05	0.13	0.70	0.34	0.12	0.00	0.23	0.12	0.05
N	94 dyads with 2623 observations														

Note: Significant associations $p < .05$ are bolded.

continued to significantly and negatively predict subsequent parent RSA ($b = -0.10$, $SE = 0.03$, $p = .006$), whereas parent RSA only marginally and positively predicted subsequent child RSA ($b = 0.08$, $SE = 0.04$, $p = .060$). We found no evidence of time-lagged synchrony in the free play, clean up, or teaching tasks.

3.3 | Between-dyad variability

To establish whether synchrony significantly varied between dyads, we included random effects in the models described above. Specifically, we tested each concurrent and time-lagged model described above, this time including a random effect for the intercept and the predictor (i.e., parent RSA). We found that the random effects were not significant for any of the concurrent or time-lagged models across the full interaction or within each task (*ps* = .09–.90). This result suggests that there was no significant variability between dyads in the level of synchrony.

We next investigated whether positive parent–child behavioral co-regulation was related to both between- and within-dyad physiological synchrony. The cross-level interaction term and Level 2 interaction term were not significant, suggesting that positive parent–child behavioral co-regulation was not related to between- or within-dyad physiological synchrony, across the full interaction or in any individual task (*ps* = .31–.97).

In follow-up sensitivity analyses, we also tested all of the models described above with the inclusion of family socioeconomic status as a covariate. All results remained identical.

4 | DISCUSSION

This study investigated whether kindergarten children and their parents exhibit concurrent and time-lagged physiological synchrony over the course of shared, dyadic interaction. Further, we examined whether the presence and nature of parent–child physiological synchrony varied by the type of interaction task, and whether positive parent–child behavioral co-regulation was associated with concurrent and time-lagged synchrony. Only during the teaching task, parent and child RSA concurrently and positively synchronized within 30-s epochs. Only during the problem-solving task, parent and child RSA appeared to reciprocally influence each other in opposite directions across subsequent 30-s epochs. We did not find evidence that dyadic physiological synchrony is associated with between-dyad differences in behavioral co-regulation. Our findings extend growing interest in understanding parent–child physiological synchrony to kindergarten age (Davis et al., 2018). Moreover, our findings suggest that physiological synchrony may be more useful as a biomarker for examining change within parent–child dyads across time or contexts, rather than individual differences between dyads.

4.1 | Dyadic teaching interaction: A context for concurrent RSA synchrony

Only during the teaching task, we found that fluctuations in parent and child RSA co-occurred in a positive, concurrent fashion. Specifically, during 30-s periods when parent RSA was higher than average, their child's RSA was simultaneously also higher than average. This result was robust to the average-level correlation between parent and child RSA, which could be influenced by underlying shared biology or environmental experiences, as well as parent and child individualized responses to the task. In contrast, during free play, clean up, and problem-solving tasks, parent and child RSA did not show concurrent synchrony.

During the teaching task, parents were asked to guide and support their child in completing challenging geometric puzzles. This type of teaching and learning activity might entail joint attention, simultaneous engagement, and synchronized behavioral responses between parent and child, which in turn might facilitate concurrent, shared patterns of physiological arousal. Overall, parents may strive to be attuned to their child's response to the challenge and respond in turn with feedback, guidance, and instruction. Conversely, children may watch their parent's demonstration and listen to their parent's verbal cues. In this way, shared attention on the structured learning activity may facilitate shared, simultaneous patterns of parent and child physiological arousal. In contrast, parent and child physiological arousal may not synchronize during more individualized tasks that do not necessarily promote high levels of joint attention, such as free play or clean up.

Some prior research suggests that concurrent synchrony differs depending on how much close, shared attention the dyadic task facilitates. Preschoolers and parents showed concurrent heart rate synchrony during a structured, collaborative drawing task, but not during a baseline period when child and parent sat quietly side by side (Suveg et al., 2016). In another sample, preschoolers with high levels of externalizing behaviors showed stronger concurrent RSA synchrony with their parents during a dyadic teaching task compared to free play and clean up (Lunkenheimer et al., 2018). However, the same study also showed that preschoolers with "low" externalizing behaviors showed weaker concurrent RSA synchrony during the structured teaching task, compared to free play and clean up, perhaps because they were able to regulate their own behavior more effectively and engage in the learning opportunity more independently (Lunkenheimer et al., 2018). Future research should further investigate whether the strength of physiological synchrony is contingent on the structure of the task, and the quality of teaching and joint attention and individual differences in child behavior.

4.2 | Problem-solving dyadic interaction: A context for time-lagged RSA synchrony

We found time-lagged synchrony during the problem-solving task only. Specifically, parent RSA "positively" predicted subsequent child RSA (30 s later), whereas child RSA "negatively" predicted subsequent parent RSA. These bidirectional associations illustrated a rise-and-fall pattern. For example, increases in parent RSA predicted subsequent increases in child RSA, which in turn predicted subsequent decreases in parent RSA. This finding suggests that while discussing solutions together, changes in parent and child physiological arousal precede each other, and may bidirectionally influence each other. In contrast, during free play, clean up, and teaching tasks, parent and child RSA did not synchronize in a time-lagged fashion.

If young children are behaviorally attuned to and following the parent's directions and cues during the discussion, changes in children's underlying physiology may follow changes in their parent's physiology. Matching patterns of physiology might support parents' and children's emotional and behavioral attunement in the moment, whereas the parent strives to engage the child and they work together (Feldman, 2006). Subsequently, once child physiological arousal has increased or decreased and more closely matches the parent's physiological arousal, parent physiological arousal may change in the opposite direction, such that it returns closer to baseline. Thus, the observed pattern of time-lagged physiological synchrony may reflect how parent–child dyads adjust their physiology in response to the states of their partner. In particular, time-lagged synchrony may emerge during our problem-solving task (rather than concurrent synchrony) because the problem-solving task involves a back-and-forth verbal discussion, or "give and take," rather than simultaneous engagement on a single shared activity (e.g., the tangos game from our teaching task). Because these physiological changes likely occur unconsciously, future research should clarify the extent to which changes in RSA map onto parents' and children's subjective emotional and cognitive experiences.

Our sensitivity analysis showed that when controlling for levels of RSA 30 s prior, parent RSA only predicted subsequent child RSA, whereas child RSA did not predict subsequent parent RSA during the problem-solving task. This pattern of synchrony could be indicative of parents taking a more leading role in discussing and solving a problem since they chose it, whereas children followed their parent's lead. This finding and interpretation is consistent with two prior studies of preschoolers and adolescents, which showed time-lagged parent–child RSA synchrony such that parent RSA positively predicted subsequent child RSA, but child RSA did not predict subsequent parent RSA (Helm et al., 2018; McKillip & Connel, 2018).

4.3 | No link between behavioral co-regulation and physiological synchrony

Our test of random effects indicated that there was no significant between-dyad variability in the level of concurrent or time-lagged RSA synchrony. Further, between-dyad differences in behavioral co-regulation were not associated with either parent–child physiological synchrony (i.e., within dyads) or the average-level correlation between parent and child RSA (i.e., between dyads). This result may be considered surprising because both physiological synchrony and behavioral co-regulation were initially conceptualized as markers of responsive parent–child interactions (Feldman, 2006). However, there is growing evidence that stronger, more positive physiological synchrony is not always associated with positive parent and child adaptation (e.g., Creavy, Gatzke-Kopp, Zhang, Fishbein, & Kiser, 2020). Our finding highlights two characteristics of physiological synchrony. First, physiological synchrony may depend more on the *structure* of the interaction task (e.g., teaching task vs. free play) compared to the *quality* of dyadic interaction (e.g., displayed behaviors of mutual responsivity, parental positive control). Regardless of whether the parent is behaviorally exhibiting positive, supportive control toward the child, he or she may engage in physiologically synchronized interactions with the child. Future research should further investigate whether other features of the parent–child relationship (e.g., psychological stress, conflict) are associated with the nature and timing of physiological synchrony.

Second, physiological synchrony may be a more useful biomarker for measuring change "within" dyads over time, compared to individual differences between dyads. Future work may identify momentary changes in shared physiological processes that, within and across sessions, can quantify contextual change within a dyad over time. For instance, shared physiological processes could act as markers of intervention effectiveness (Granic et al., 2007). Moreover, measuring physiological synchrony may inform the design of innovative parenting interventions that seek to change maladaptive parent–child interaction patterns by targeting and reinforcing small positive moments in dyadic interactions (Fisher et al., 2016). Dynamic understanding of physiological contingencies could shed light on key moments in which to intervene.

It is possible that individual differences in dyadic behavior are related to synchrony in other physiological systems that we did not measure—such as heart rate, which is influenced by both the parasympathetic and sympathetic branches. In one study of infants and parents, heart rate synchrony increased significantly during seconds when maternal and child affect and vocalizations were more matched during a free play task, compared to when affect and vocalizations were less matched (Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011). Because that study measured both affect and synchrony on a second-to-second basis and used only within-dyad analysis via autoregressive models, significant between-dyad variability was not a necessary prerequisite for their analyses. Future research should attempt to replicate these within-dyad associations between physiological synchrony and parent–child co-regulation at kindergarten age. On the one hand, physiological synchrony and parent–child co-regulation may be related on a second-by-second basis during infancy but not during kindergarten age, when children are relatively more independent. On the other hand, physiological synchrony and parent–child co-regulation may be related on a second-by-second basis also during kindergarten, because kindergartners are still closely attuned to and reliant on their parents.

In addition, future research should simultaneously measure dyadic behavior and differentiate between both the sympathetic and parasympathetic branches, for example, by measuring pre-ejection period and RSA, respectively, in longitudinal samples. Future research should also further investigate a wider range of child and parent experiences that might interplay with synchrony, such as experiences of parent–child conflict or maltreatment (e.g., Creaven, Skowron, Hughes, Howard, & Loken, 2014). For instance, one study suggested that physiological synchrony was protective among 5-year-old children with a history of trauma (Gray, Lipschutz, & Scheeringa, 2018). Finally, future research should consider how different methodological and statistical approaches influence the ability to detect relations among behavioral co-regulation and physiological synchrony. For example, analytical methods that use continuous time series and second-by-second coding may reveal previously undetected associations between behavioral co-regulation and physiological synchrony (Gates & Liu, 2016). This method would necessitate extremely precise second-by-second pairing of physiological and behavioral data (Gates & Liu, 2016). Future research may also explore associations between behavioral co-regulation and nonlinear indices of cardiac complexity, such as fractality and sample entropy (Berry, Palmer, Distefano, & Masten, 2019).

4.4 | Limitations

We acknowledge several limitations. First, our study is correlational. Changes in one partner's physiology may co-occur or precede changes in the other without initiating a causal influence. Second, our small sample size may have limited our ability to detect statistically significant between-dyad variability in physiological synchrony as well as relations with behavioral coregulation. Our sample was similar in size to some prior studies that have found significant physiological synchrony (e.g., Helm et al., 2018; Suveg et al., 2019, 2016), but smaller than others (e.g., Fuchs, Lunkenheimer, & Lobo, 2021; Li et al., 2020; Lunkenheimer, Brown, & Fuchs, 2021). Future research should replicate our findings in larger samples to clarify whether shared patterns of behavior are associated with RSA synchrony. Third, and relatedly, in our study only seven primary caregivers were men, which was a too small subsample to examine how physiological synchrony differed by primary caregiver gender. Future research should investigate parental gender differences, to extend prior work examining parental gender differences in the level of synchrony during adolescence (Li et al., 2020) and at age three (Lunkenheimer et al., 2021) to kindergarten age. Fourth, our study was cross-sectional. Examining physiological synchrony across development in future longitudinal research may help to clarify whether physiological synchrony meaningfully differs across dyads as has been observed in some prior studies of older youth (Amole et al., 2017; Li et al., 2020; Skoranski et al., 2017), but not at kindergarten age, as we observe. Finally, future research should test whether there is significant between-dyad variability in physiological synchrony in other samples, and whether this variability is associated with various forms of stress and adversity. For instance, prior research suggests that concurrent synchrony is positive among nondepressed mothers and their adolescents (i.e., increases in parental RSA are linked to simultaneous increases in youth RSA), whereas concurrent synchrony is negative among depressed mothers and their adolescents (i.e., increases in parental RSA are linked to simultaneous decreases in youth RSA; Woody et al., 2016). Future work could investigate whether parental depression, as well as other forms of stress and adversity, similarly moderates synchrony at kindergarten age.

5 | CONCLUSION

Previous research on parasympathetic synchrony has largely focused on samples of infants, preschoolers, and adolescents, and studies of kindergartners have been limited to at-risk samples that experienced severe trauma or maltreatment (Creaven et al., 2014; Gray et al., 2018). We extend this work to investigate physiological synchrony in a community sample of kindergartners, who are still reliant on their parents, but also independently face new daily activities and challenges that require internalized self-regulated behavior (Calkins, 2011). Our results suggest that fluctuations in parent and child RSA co-occur during a teaching task, and reciprocally influence each other across subsequent 30-s periods during a problem-solving task. Although behavioral co-regulation and physiological synchrony have both been conceptualized as markers of responsive parent–child interactions (Feldman, 2006), we did not find meaningful variability between dyads and did not find that synchrony was related to parent–child behavioral co-regulation. Our study contributes to the developmental literature by illustrating that parent–child physiological synchrony may be more closely linked to the structure and type of interaction than to dyadic differences in observable behaviors. Moreover, physiological synchrony may provide insight as a biomarker for measuring change in reciprocal processes within parent–child dyads over time. For example, physiological synchrony may be useful for quantifying developmental changes, or contextual changes within dyads over time, which might shed light on when and how to support children's positive adaptation.

ACKNOWLEDGEMENTS

The preparation of this article was supported by a Jacobs Foundation Advanced Research Fellowship grant 2017-1261-07 to Dr. Jelena Obradovic; a doctoral fellowship to Emma Armstrong-Carter funded by the Institute of Education Sciences, U.S. Department of Education, through Grant R305B140009 to the Board of Trustees of the Leland Stanford Junior University, and the Stanford Data Science Fellowship awarded to Emma Armstrong-Carter.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data for this manuscript and syntax are available upon request.

ORCID

Emma Armstrong-Carter https://orcid.org/0000-0002-5847-9486
Jonas G. Miller https://orcid.org/0000-0001-7061-3900
Jelena Obradović https://orcid.org/0000-0001-7405-4608

REFERENCES

Amole, M. C., Cyranowski, J. M., Wright, A. G. C., & Swartz, H. A. (2017). Depression impacts the physiological responsiveness of mother-daughter dyads during social interaction. *Depression and Anxiety*, *34*(2), 118–126. https://doi.org/10.1002/da.22595

Armstrong-Carter, E., Sulik, M. J., & Obradović, J. (2021). Self-regulated behavior and parent-child co-regulation are associated with young children's physiological response to receiving critical adult feedback. *Social Development*, *30*(3), 730–747. https://doi.org/10.1111/sode.12498

Bardack, S., Herbers, J. E., & Obradović, J. (2017). Unique contributions of dynamic versus global measures of parent–child interaction quality in predicting school adjustment. *Journal of Family Psychology*, *31*, 649–658. https://doi.org/10.1037/fam0000296

Bar-Haim, Y., Marshall, P. J., & Fox, N. A. (2000). Developmental changes in heart period and high-frequency heart period variability from 4 months to 4 years of age. *Developmental Psychobiology*, *37*(1), 44–56. https://doi.org/10.1002/1098-2302(200007)37:1<44::AID-DEV6>3.0.CO;2-7

Berry, D., Palmer, A. R., Distefano, R., & Masten, A. S. (2019). Autonomic complexity and emotion (dys-)regulation in early childhood across high- and low-risk contexts. *Development and Psychopathology*, *31*(3), 1173–1190. https://doi.org/10.1017/S0954579419000683

Calkins, S. D. (2011). Caregiving as coregulation: Psychobiological processes and child functioning. In A. Booth, S. M. McHale, & N. S. Landale (Eds.), *Biosocial foundations of family processes* (pp. 49–59). Springer New York. https://doi.org/10.1007/978-1-4419-7361-0_3

Creaven, A.-M., Skowron, E. A., Hughes, B. M., Howard, S., & Loken, E. (2014). Dyadic concordance in mother and preschooler resting cardiovascular function varies by risk status: Cardiovascular concordance in mother-child dyads. *Developmental Psychobiology*, *56*(1), 142–152. https://doi.org/10.1002/dev.21098

Creavy, K. L., Gatzke-Kopp, L. M., Zhang, X., Fishbein, D., & Kiser, L. J. (2020). When you go low, I go high: Negative coordination of physiological synchrony among parents and children. *Developmental Psychobiology*, *62*(3), 310–323. https://doi.org/10.1002/dev.21905

Curran, P. J., & Bauer, D. J. (2011). The disaggregation of within-person and between-person effects in longitudinal models of change. *Annual Review of Psychology*, *62*(1), 583–619. https://doi.org/10.1146/annurev.psych.093008.100356

Davis, M., West, K., Bilms, J., Morelen, D., & Suveg, C. (2018). A systematic review of parent-child synchrony: It is more than skin deep. *Developmental Psychobiology*, *60*(6), 674–691. https://doi.org/10.1002/dev.21743

Feldman, R. (2006). From biological rhythms to social rhythms: Physiological precursors of mother-infant synchrony. *Developmental Psychology*, *42*(1), 175–188. https://doi.org/10.1037/0012-1649.42.1.175

Feldman, R., Magori-Cohen, R., Galili, G., Singer, M., & Louzoun, Y. (2011). Mother and infant coordinate heart rhythms through episodes of interaction synchrony. *Infant Behavior and Development*, *34*(4), 569–577. https://doi.org/10.1016/j.infbeh.2011.06.008

Fisher, P. A., Beauchamp, K. G., Roos, L. E., Noll, L. K., Flannery, J., & Delker, B. C. (2016). The neurobiology of intervention and prevention in early adversity. *Annual Review of Clinical Psychology*, *12*(1), 331–357. https://doi.org/10.1146/annurev-clinpsy-032814-112855

Fuchs, A., Lunkenheimer, E., & Lobo, F. (2021). Individual differences in parent and child average RSA and parent psychological distress influence parent-child RSA synchrony. *Biological Psychology*, *161*, 108077. https://doi.org/10.1016/j.biopsycho.2021.108077

Gates, K. M., & Liu, S. (2016). Methods for quantifying patterns of dynamic interactions in dyads. *Assessment*, *23*(4), 459–471. https://doi.org/10.1177/1073191116641508

Granic, I., O'Hara, A., Pepler, D., & Lewis, M. D. (2007). A dynamic systems analysis of parent–child changes associated with successful "real-world" interventions for aggressive children. *Journal of Abnormal Child Psychology*, *35*(5), 845–857. https://doi.org/10.1007/s10802-007-9133-4

Gray, S. A. O., Lipschutz, R. S., & Scheeringa, M. S. (2018). Young children's physiological reactivity during memory recall: Associations with posttraumatic stress and parent physiological synchrony. *Journal of Abnormal Child Psychology*, *46*(4), 871–880. https://doi.org/10.1007/s10802-017-0326-1

Helm, J. L., Miller, J. G., Kahle, S., Troxel, N. R., & Hastings, P. D. (2018). On measuring and modeling physiological synchrony in dyads. *Multivariate Behavioral Research*, *53*(4), 521–543. https://doi.org/10.1080/00273171.2018.1459292

Lamey, A., Hollenstein, T., Lewis, M. D., & Granic, I. (2004). *Gridware (Version 1.1)*. http://www.statespacegrids.org

Li, Z., Sturge-Apple, M. L., Liu, S., & Davies, P. T. (2020). Parent-adolescent physiological synchrony: Moderating effects of adolescent emotional insecurity. *Psychophysiology*, *57*(9), e13596. https://doi.org/10.1111/psyp.13596

Lunkenheimer, E., Brown, K. M., & Fuchs, A. (2021). Differences in mother–child and father–child RSA synchrony: Moderation by child self-regulation and dyadic affect. *Developmental Psychobiology*, *63*(5), 1210–1224. https://doi.org/10.1002/dev.22080

Lunkenheimer, E., Hamby, C. M., Lobo, F. M., Cole, P. M., & Olson, S. L. (2020). The role of dynamic, dyadic parent–child processes in parental socialization of emotion. *Developmental Psychology*, *56*(3), 566–577. https://doi.org/10.1037/dev0000808

Lunkenheimer, E., Kemp, C. J., Lucas-Thompson, R. G., Cole, P. M., & Albrecht, E. C. (2017). Assessing biobehavioural self-regulation and coregulation in early childhood: The parent-child challenge task. *Infant and Child Development*, *26*(1), e1965. https://doi.org/10.1002/icd.1965

Lunkenheimer, E., Tiberio, S. S., Buss, K. A., Lucas-Thompson, R. G., Boker, S. M., & Timpe, Z. C. (2015). Coregulation of respiratory sinus arrhythmia between parents and preschoolers: Differences by children's externalizing problems. *Developmental Psychobiology*, *57*(8), 994–1003. https://doi.org/10.1002/dev.21323

Lunkenheimer, E., Tiberio, S. S., Skoranski, A. M., Buss, K. A., & Cole, P. M. (2018). Parent-child coregulation of parasympathetic processes varies by social context and risk for psychopathology. *Psychophysiology*, *55*(2), e12985. https://doi.org/10.1111/psyp.12985

MacPhee, D., Lunkenheimer, E., & Riggs, N. (2015). Resilience as regulation of developmental and family processes. *Family Relations*, *64*(1), 153–175. https://doi.org/10.1111/fare.12100

McKillop, H. N., & Connell, A. M. (2018). Physiological linkage and affective dynamics in dyadic interactions between adolescents and their mothers. *Developmental Psychobiology*, *60*(5), 582–594. https://doi.org/10.1002/dev.21630

Moore, G. A. (2009). Infants' and mothers' vagal reactivity in response to anger. *Journal of Child Psychology and Psychiatry*, *50*(11), 1392–1400. https://doi.org/10.1111/j.1469-7610.2009.02171.x

Obradović, J., & Boyce, W. T. (2012). Stress reactivity in child development research. In L. Mayes & M. Lewis (Eds.), *The Cambridge handbook of environment in human development* (pp. 655–681). Cambridge University Press. https://doi.org/10.1017/CBO9781139016827.036

Ostlund, B. D., Measelle, J. R., Laurent, H. K., Conradt, E., & Ablow, J. C. (2017). Shaping emotion regulation: Attunement, symptomatology, and stress recovery within mother-infant dyads. *Developmental Psychobiology*, *59*(1), 15–25. https://doi.org/10.1002/dev.21448

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology*, *74*(2), 116–143. https://doi.org/10.1016/j.biopsycho.2006.06.009

Pratt, M., Singer, M., Kanat-Maymon, Y., & Feldman, R. (2015). Infant negative reactivity defines the effects of parent–child synchrony on physiological and behavioral regulation of social stress. *Development and Psychopathology*, *27*(4pt1), 1191–1204. https://doi.org/10.1017/S0954579415000760

Rudolph, S., Rudolph, A., Hostetter, M., Lister, G., & Siegel, N. (2003). *Rudolph's pediatrics* (21st ed.). McGraw-Hill Medical.

Scholtes, C. M., Lyons, E. R., & Skowron, E. A. (2021). Dyadic synchrony and repair processes are related to preschool children's risk exposure and self-control. *Development and Psychopathology*, *33*(3), 1072–1084. https://doi.org/10.1017/S0954579420000358

Skoranski, A. M., Lunkenheimer, E., & Lucas-Thompson, R. G. (2017). The effects of maternal respiratory sinus arrhythmia and behavioral engagement on mother-child physiological coregulation. *Developmental Psychobiology*, *59*(7), 888–898. https://doi.org/10.1002/dev.21543

Smith, J. D., Woodhouse, S. S., Clark, C. A., & Skowron, E. A. (2016). Attachment status and motherpreschooler parasympathetic response to the strange situation procedure. *Biological psychology*, *114*, 39–48. https://doi.org/10.1016/j.biopsycho.2015.12.008

Suveg, C., Braunstein West, K., Davis, M., Caughy, M., Smith, E. P., & Oshri, A. (2019). Symptoms and synchrony: Mother and child internalizing problems moderate respiratory sinus arrhythmia concordance in mother–preadolescent dyads. *Developmental Psychology*, *55*(2), 366–376. https://doi.org/10.1037/dev0000648

Suveg, C., Shaffer, A., & Davis, M. (2016). Family stress moderates relations between physiological and behavioral synchrony and child self-regulation in mother-preschooler dyads: Physiological synchrony in mother-child dyads. *Developmental Psychobiology*, *58*(1), 83–97. https://doi.org/10.1002/dev.21358

Wang, L., & Maxwell, S. E. (2015). On disaggregating between-person and within-person effects with longitudinal data using multilevel models. *Psychological Methods*, *20*(1), 63–83. https://doi.org/10.1037/met0000030

Woody, M. L., Feurer, C., Sosoo, E. E., Hastings, P. D., & Gibb, B. E. (2016). Synchrony of physiological activity during mother-child interaction: Moderation by maternal history of major depressive disorder. *Journal of Child Psychology and Psychiatry*, *57*(7), 843–850. https://doi.org/10.1111/jcpp.12562

How to cite this article: Armstrong-Carter, E., Miller, J. G., & Obradović, J. (2021). Parent–child physiological synchrony: Concurrent and lagged effects during dyadic laboratory interaction. *Developmental Psychobiology*, *63*, e22196. https://doi.org/10.1002/dev.22196