

RESEARCH ARTICLE

Physiological and social synchrony as markers of PTSD and resilience following chronic early trauma

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Abstract

Objective: Although resilience is a key topic in clinical theory and research, few studies focused on biobehavioral mechanisms that underpin resilience. Guided by the *biobehavioral synchrony* frame, we examined the dynamic interplay of physiological and behavioral synchrony as marker of risk and resilience in trauma-exposed youth.

Methods: A unique cohort of war-exposed versus control children was followed at four time-points from early childhood to preadolescence and child posttraumatic stress disorder (PTSD) repeatedly assessed. At preadolescence (11–13 years), mother and child were observed in several social and nonsocial tasks while cardiac data collected and measures of respiratory sinus arrhythmia (RSA) and RSA synchrony computed. The social interactive task was microcoded for behavioral synchrony and the second-by-second balance of behavioral and physiological synchrony was calculated. War-exposed preadolescents were divided into those diagnosed with PTSD at any time-point across childhood versus resilient children.

Results: Group differences in behavioral synchrony, RSA synchrony, and their interplay emerged. PTSD dyads exhibited the tightest autonomic synchrony combined with the lowest behavioral synchrony, whereas resilient dyads displayed the highest behavioral and lowest autonomic synchrony. Hierarchical Linear Model analysis pinpointed two resilience-promoting mechanisms. First, for resilient and control dyads, moments of behavioral synchrony were coupled with decreased RSA synchrony. Second, only among resilient dyads, moments of behavioral synchrony increased child RSA levels.

Conclusion: Findings specify mechanisms by which biobehavioral synchrony promotes resilience. As children grow, the tightly coupled mother–child physiology must be replaced by loosely coordinated behavioral attunement that buttresses maturation of the child's allostatic self-regulation. Our findings highlight the need for synchrony-based interventions to trauma-exposed mothers.

KEYWORDS

biobehavioral synchrony, longitudinal studies, mother child relationship, posttraumatic stress disorder (PTSD), respiratory sinus arrhythmia

1 | INTRODUCTION

Although resilience is a central concept in clinical theory and research, understanding its development is still limited and, to date, few studies followed children over lengthy periods to define factors that distinguish children reared amidst adversity who develop psychopathology from those growing up in similar contexts who are more resilient. Conceptual models on resilience (Masten & Narayan, 2012; Rutter, 2012) suggest that components of the child's biology interact with caregiving patterns to confer resilience; yet, little research has tested theoretically informed resilience-promoting mechanisms related to caregiving. Overall, three important issues still require much further attention in resilience research. First, models on resilience (Kalisch et al., 2017; Rutter, 2013) have indicated that to further understand resilience, research should follow children longitudinally to assess how resilience is uniquely expressed at critical developmental nodes but such studies are rare. Second, while the development of resilience rests on the child's relationship with the caregiver (Feldman, 2020), very few studies included direct observations of caregiving to specify dyadic mechanisms that sustain resilience. Finally, most research on resilience examined an umbrella of risk conditions, grouped under the terms "early life stress" (ELS) or "toxic stress" (Shonkoff et al., 2012); however, these include highly heterogeneous groups which limit our capacity to pinpoint condition-specific mechanisms of resilience. To advance research on resilience and develop interventions to foster it, studies should target specific mechanisms related to the biology-caregiving interface, follow children over lengthy periods, and tease apart conditions that are currently lumped under the global term of ELS.

In the current study, we targeted a specific dyadic mechanism proposed to play a key role in resilience—*biobehavioral synchrony* (Feldman, 2017, 2020)—and tested its expression in a group of preadolescents exposed to war-related trauma since birth who were followed from early childhood to early adolescence in comparison with nonexposed controls. Children growing up amidst chronic trauma were divided into two subgroups: those who developed posttraumatic stress disorder (PTSD) at some point across childhood versus those exposed to similar external stressors who did not develop the disorder. In preadolescence, mother and child were observed in several interactive contexts while cardiac and behavioral data collected. We were specifically interested in the balance between autonomic and behavioral synchrony in the three groups and how such balance may index risk versus resilience.

Biobehavioral synchrony is a key mechanism by which human infants are ushered into the social world. Defined as "the coordination of biological and behavioral processes between mother and child during moments of social contact" (Feldman, 2017, p. 81), biobehavioral synchrony is the mechanism by which attachment bonds become dyad-specific and long-lasting across social development (Feldman, 2015, 2017). Biobehavioral synchrony marks a behavior-based mechanism for the mutual entrainment of physiological processes, particularly heart and brain rhythms (Feldman, Magori-Cohen, Galili, et al., 2011; Kinreich et al., 2017). Furthermore,

biobehavioral synchrony plays a key role in resilience due to its contribution to the three tenets of human resilience: neural and behavioral plasticity, attachment and sociality, and the capacity to attribute meaning to trauma through acts of affiliation, kindness, and social connection (Feldman, 2020). The coupling of physiological and behavioral processes during social encounters originates within the mother–infant bond and is then transferred to other human affiliations, including couples (Helm et al., 2012), friends (Goldstein et al., 1989), and group members (Golland et al., 2015). However, although close coordination between autonomic and behavioral synchrony suggests greater resilience in infancy, as children grow tight autonomic coupling has been linked with stressed relationships (Papp et al., 2009; Pratt et al., 2017; Williams et al., 2013), suggesting that with development, mothers must relax their external regulatory role over the child's physiological systems to enable the development of self-regulation and bolster resilience.

The autonomic nervous system, which plays a key role in the body's homeostatic function, integrates two branches, the sympathetic and parasympathetic (PNS) nervous systems (Zisner & Beauchaine, 2016). The PNS plays an inhibitory role and underpins emotional regulation and flexible adaptation to changing environmental conditions (Beauchaine, 2015; Porges, 2007). Respiratory sinus arrhythmia (RSA), which measures parasympathetic influences over heart rhythms, serves as a reliable index of parasympathetic activity (Porges, 2007) and has been shown to predict risk and resilience (Gentzler et al., 2009; Yaptangco et al., 2015). Higher resting RSA facilitates engagement, promotes social competencies, and enhances flexibility (Beauchaine, 2001; Muhtadie et al., 2015), whereas low resting RSA is linked with high-risk rearing, disrupted mother–child relationships (Feldman, 2006), and psychopathology in children, adolescents, and adults (Beauchaine & Thayer, 2015; Shahrestani et al., 2014).

In addition to extant research on RSA, increasing attention has been directed to interpartner RSA synchrony, particularly between mothers and children during social contact. In early childhood, greater RSA synchrony has been shown to index resilience. For instance, during trauma recollection, greater RSA synchrony was observed between mothers and trauma-exposed preschoolers who did not develop PTSD, compared with both PTSD children and nonexposed controls (Gray et al., 2018), and reduced mother–preschooler RSA synchrony predicted psychopathology in both mother and child (Lunkenheimer et al., 2015, 2018). However, as children grow evidence is mixed. Some studies showed lower RSA synchrony between depressed mothers and their older children and adolescents (Amole et al., 2017; Woody et al., 2016). Other studies, focused on healthy adolescents, suggest that low RSA synchrony is developmentally adaptive and is associated with children's empathic capacity. Furthermore, authors have suggested that high degree of synchrony may not be adaptive when the parent's emotional capacity is reduced (Creavy et al., 2019). Similarly, greater RSA synchrony during marital conflict has been shown to predict heightened inflammatory biomarkers and escalating modes of conflict discussion (Wilson et al., 2018). A recent review on parent–child physiological synchrony noted that RSA synchrony may be related to adaptive or

maladaptive functioning depending on the specific risk context, and emphasized the need for further studies to pinpoint both adverse and adaptive contexts. It has been further noted that research on RSA synchrony beyond early childhood is scarce and further studies are needed to address its developmental aspects (Davis et al., 2018). To date, no study on RSA synchrony has tested its ongoing coupling with behavioral synchrony in ways similar to research on cardiovascular or brain activity (Feldman, Magori-Cohen, et al., 2011; Kinreich et al., 2017). Such integration of RSA and behavioral synchrony may shed further light on these conflicting findings.

PTSD is among the few disorders that follow a distinct hazardous event (American Psychiatric Association, 2013); hence, describing individual differences in response to trauma provides a useful vantage-point for understanding resilience (Yehuda et al., 2015). Children exposed to chronic war-related trauma exhibit high rates of PTSD and severe posttraumatic profiles (Feldman & Vengrober, 2011; Halevi et al., 2016). The mother-child relationship is often compromised (Yirmiya et al., 2018) and the development of PTSD across childhood is shaped by the mother-child relationship quality (Halevi et al., 2016). As one in five children world-wide is exposed to war-related trauma resulting from national, tribal, ethnic, or regional violence, it is critical to pinpoint mechanisms that enhance resilience in such children to formulate brief and specific interventions.

To address markers of resilience related to physiological and behavioral synchrony, we followed a unique cohort of war-exposed preadolescents living in the same frontline neighborhoods in Sderot, Israel and exposed to repeated war-related trauma at four time-points (see Section 2). Our longitudinal follow-up, offers a unique “natural experiment” for the study of resilience that is often missing from samples where trauma is personal and highly variable.

Consistent with the *biobehavioral synchrony* model, three hypotheses were formulated. First, we expected that real-life social interactions would elicit the largest differences in RSA synchrony among PTSD, resilient, and control children. Second, studies have shown that tighter synchrony between maternal and child's stress-related physiology predicts less favorable outcomes (Pratt et al., 2017) and we thus expected to find tighter RSA synchrony in the PTSD group. Finally, using epoch-by-epoch analysis of mother-child biobehavioral synchrony, we searched for mechanisms by which synchrony bolsters resilience. We hypothesized that such mechanisms may lie in the balance between physiological and behavioral synchrony where increased behavioral synchrony may afford less tightly coupled autonomic synchrony to enable greater flexibility and resilience.

2 | METHODS

2.1 | Participants

In *early childhood* (T1), a total of 232 children and their mothers were recruited in 2004–2005 during early childhood ($M = 2.76$ years, $SD = 0.91$) in two groups, war-exposed and control. War exposed

group included 148 mother-child dyads residing in Sderot, a small Israeli town located few kilometers off the Gaza border whose residents have been exposed to thousands of frequent and unpredictable rockets attacks since 2000, placing them at daily threat of death or severe injury. The control group comprised 84 dyads from comparable towns in central Israel, matched for age, gender, birth order, parental age and education, maternal employment, and marital status (Feldman & Vengrober, 2011). Before home visits, control families were screened by phone for major traumatic events in the child's life (e.g., motor vehicle accidents, physical, or sexual abuse) and those reporting such trauma were excluded.

We revisited families in three additional key points: *Middle childhood* (T2: $M = 7.68$ years, $SD = 0.7$), *late childhood* (T3: $M = 9.3$ years, $SD = 1.41$), and *early adolescence* (T4: $M = 11.57$ years, $SD = 1.33$). At T4, 102 dyads who participated in all previous waves were included (53 war-exposed). Attrition was mainly related to inability to locate families. No demographic differences were found between families who did or did not participate in the current stage on any demographic variable. The study was approved by the local Institutional Review Board and all mothers signed informed consent.

2.2 | Procedure

2.2.1 | Early childhood (T1)

Mother-child dyads were visited at home and videotaped in naturalistic interactions. Child PTSD was evaluated by using Diagnostic Classification: Zero-to-Three (Zero To Three, 2005), and mothers completed self-report measures.

2.2.2 | Middle childhood (T2)

Child PTSD was diagnosed using the Developmental and Well-Being Assessment (DAWBA) administered by a trained clinician, supervised child psychiatrist, blind to any other information, with reliability more than 85% and cases conferred every few weeks. The DAWBA provides assessment for 5–17-year-old children according to International Classification of Disease-10 and Diagnostic and Statistical Manual of Mental Disorders-IV diagnoses and is well validated (Goodman et al., 2000), including in a large epidemiological study in Israel (Mansbach-Kleinfeld et al., 2010).

2.2.3 | Late childhood (T3)

Mother-child dyads were videotaped during home-visit. Child PTSD was reevaluated by DWABA. Mothers completed the Posttraumatic Diagnostic Scale, a well-validated self-report measure of adult PTSD symptoms (Foa et al., 1997).

2.2.4 | Early adolescence (T4)

Upon arrival, mother and child were connected to Mindware device (Mindware Technologies Ltd.) that continuously and simultaneously recorded electrocardiogram (ECG), respiration data (RSP), video, and audio from both. Dyads were videoed in three tasks. (a) *Baseline*: mother and child sit next to each other and asked to relax and not interact for 3 min. (b) *Interaction*: mother and child engaged in a joint interaction using “Etch-a-sketch” where each held different control knob and the two copied a house presented on paper. (c) *Attachment reminders*: dyads watched 4-min video clips of their past interactions during early and late childhood.

2.3 | Measures

2.3.1 | Behavioral synchrony

Interactions were microcoded offline in 0.1 s frame using computerized system (Noldus, Wageningen, Netherlands). Coding was based on our prior research and considered key modules of non-verbal behavior; gaze, affect, vocalization, and touch (Feldman, 2017). Coding was performed separately for mother and child by trained coders blind to other information with inter-rater reliability performed on 10% of interactions showing 96% agreement ($k = .87$). *Behavioral synchrony* was marked as moments when mother and child shared a joint gaze to the toy, combined with joint laughter or positive effect or moments of shared social gaze concurring with joint positive effect or laughter. Two types of measures were extracted: *proportion of time* dyads exhibited behavioral synchrony, and the exact time-frames where synchrony occurred during the interaction, which was used as template for measuring RSA synchrony.

2.3.2 | Physiological data

Mother's and child's ECG and RSP signals were collected simultaneously using MindWare's Bionex device. ECG was recorded using modified Lead II configuration and RSP with respiratory belt placed around the chest. ECG and RSP data were sampled at 1000 Hz. Data were transmitted to computer in adjacent room monitored by research assistant and captured using BioLab Software version 3.0 (MindWare Technologies Ltd.). Data were processed offline using HRV 3.0.21 software (Mindware Technologies Ltd.). ECG data were visually inspected for artifacts, missing heartbeats were manually deleted or inserted as appropriate. Data of participants with more than 10% problematic R-waves were excluded.

2.3.3 | RSA estimation

RSA was calculated separately for each task. Using the *RHRV* package for R software version 3.6 (R Foundation), we interpolated each

subject's IBI series to obtain equally spaced heart rate time series at 33 Hz. Data were then tapered with Hanning window and submitted to Fast Fourier Transform to derive the spectral distribution. RSA was quantified as the integral power within the respiratory frequency band (0.12–0.40 Hz for mothers (Cacioppo et al., 2007) and 0.2–0.42 Hz for children (Fleming et al., 2011)).

2.3.4 | Continuous RSA synchrony

We adopted Gates et al.'s (2015; see also Wilson et al., 2018) procedure for estimating dyadic RSA synchrony. Specifically, the *RHRV* R-package was used to apply a Short-Time Fourier transform to produce 1-s estimates of RSA from 32-s consecutive windows. In a second step, each HRV series was differenced (at lag-4) to remove linear trends in the data. Finally, we computed the lag-0 cross-correlation within each dyad differenced RSA time-series (Figure 1). The correlation estimates were transformed using Fisher z-transformation to normalize the distribution.

2.3.5 | Second-by-second association of mother-child RSA synchrony and behavioral synchrony

To align behavioral and RSA synchrony, we computed a moving average of the behavioral synchrony data using 32-s consecutive windows.

2.4 | Statistical analyses

Data were exported to SPSS 23 (IBM Corp.). Group differences were examined using analysis of variance (ANOVA) for the continuous variables and χ^2 for the categorical variables. All post hoc comparisons were Bonferroni corrected.

Hierarchical Linear Model (HLM) was used to assess the temporal association between behavioral and RSA synchrony co-occurrence. In this model, the child's second-level RSA was entered as a dependent variable and mother's RSA as a predictor. We used seconds-level behavioral synchrony as well as the group as moderators. We also included the three-way interaction between child's RSA, behavioral synchrony, and group, to test whether the temporal association between behavioral and RSA synchrony differed among the dyads' in the three groups. Level-1 predictors were person-mean centered and treated as random effects (Bolger & Laurenceau, 2013). Lag-1 auto-regressive structure was imposed on level-1 residuals.

Ten dyads in the baseline task and 17 in the attachment reminders did not have valid RSA data due to excessive movement artifacts or device failure. The first 5 min of the interaction task was used for analysis and only dyads that interacted longer than 2 min were included (9 removed for insufficient length and 13 for no valid RSA data).

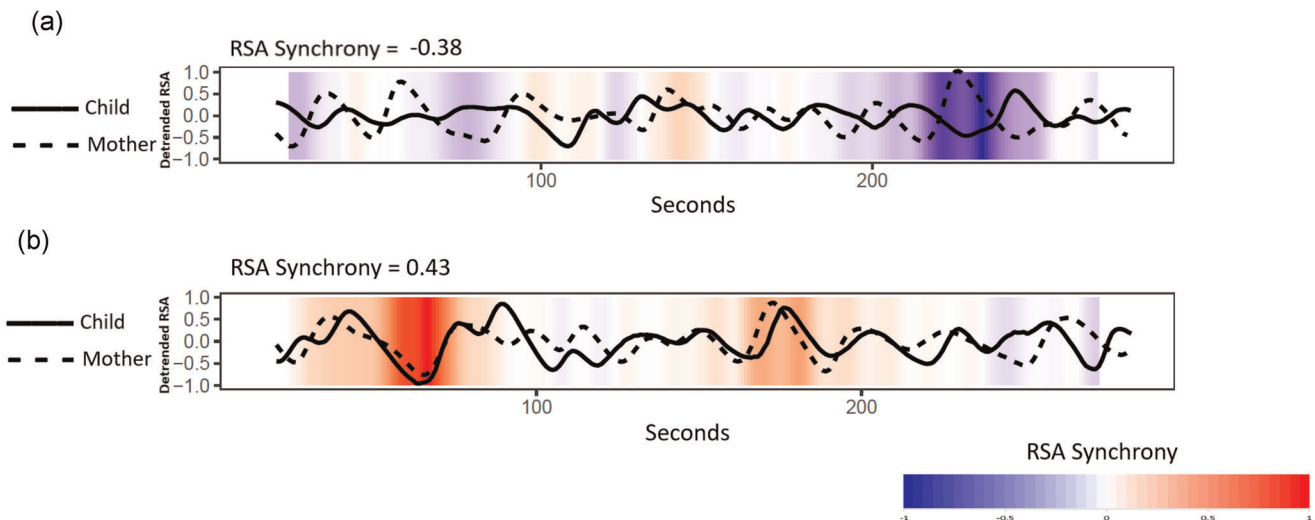


FIGURE 1 Illustration of two mother–child dyads depicting dynamic changes in detrended RSA time-series and RSA synchrony across the social interaction task. Note: (a) *Low-synchrony dyad*. Mother and child decoupled their dynamic RSA pattern during most of the social task. Overall, child exhibited dynamic RSA pattern that contrasted the mother's dynamic RSA pattern. When child augmented or suppressed parasympathetic activity, mother presented the opposite pattern. (b) *High synchrony dyad*. Mother and child exhibited a tightly coupled dynamic RSA pattern during most of the social task. Overall, child exhibited dynamic RSA pattern that mirrored the mother's dynamic RSA pattern. Red background indicates a period of amplified RSA synchrony and blue background a period of amplified RSA dyssynchrony. PTSD, posttraumatic stress disorder; RSA, respiratory sinus arrhythmia

3 | RESULTS

Of the 53 war-exposed children, 27 (51%) met PTSD diagnosis criteria at least once across childhood and these comprised the Exposed-PTSD group (named hereafter PTSD), while the other exposed dyads were the Exposed-no-PTSD group (named hereafter resilient). Among the PTSD group, 74% of the children met diagnosis criteria at one-time point, 15% met criteria in two-time point, and 11% met criteria in all three-time points. Sociodemographic information for the three groups appears in Table 1 and shows no group differences.

Group difference emerged in mothers' posttraumatic symptoms; $F_{2,96} = 12.743$, $p < .001$, (Table 1). Post hoc comparisons indicated that mothers of PTSD children reported significantly more PTSD

symptoms compared with mothers of resilient children ($p = .014$) and controls ($p < .001$). No difference emerged between mothers of resilient and control groups ($p = .256$).

Two ANOVAs assessing mother's and child's RSA with group as the between-subject factor showed no difference for mother or child (Table 1).

3.1 | Mother–child RSA synchrony

ANOVA for the interaction task showed significant group difference; $F_{2,77} = 3.197$, $p = .046$ (Figure 2). Post hoc comparisons indicated that resilient dyads had lower RSA synchrony compared

TABLE 1 Comparison on child and mother sociodemographic variables, baseline RSA, and mother PDS scores between the groups

| Characteristic | PTSD ($n = 27$) | | Resilient ($n = 26$) | | Control ($n = 49$) | | Statistics |
|----------------------------------|--------------------|---------|------------------------|--------|----------------------|--------|---------------------------------|
| Child | | | | | | | |
| Age, mean (SD) | 11.82 | (1.23) | 11.53 | (1.55) | 11.45 | (1.25) | $F_2 = 0.69$ ($p = .50$) |
| Girls, N | 13 | (48%) | 10 | (38%) | 32 | (65%) | $\chi^2_2 = 5.42$ ($p = .07$) |
| Baseline RSA, mean (SD) | 5.58 | (1.26) | 5.65 | (1.19) | 5.48 | (1.12) | $F_2 = 0.18$ ($p = .84$) |
| Mother | | | | | | | |
| Age, mean (SD) | 41.5 | (4.98) | 39.22 | (6.23) | 41.14 | (4.66) | $F_2 = 1.56$ ($p = .21$) |
| Education, N High-school/above | 7 | (26%) | 7 | (27%) | 7 | (14%) | $\chi^2_2 = 2.30$ ($p = .32$) |
| Married, N | 26 | (96%) | 23 | (88%) | 45 | (92%) | $\chi^2_2 = 1.14$ ($p = .57$) |
| PDS score, mean (SD) | 10.18 ^a | (12.54) | 4.23 ^b | (6.10) | 1.04 ^b | (2.74) | $F_2 = 12.74$ ($p < .001$) |
| Baseline RSA, mean (SD) | 4.97 | (1.09) | 5.31 | (0.77) | 5.15 | (1.14) | $F_2 = 0.70$ ($p = .50$) |

Note: Results that were statistically significant are in bold. The means followed by the different superscript letters in the same line are significantly different ($p < .05$).

Abbreviations: PDS, posttraumatic diagnostic scale; RSA, respiratory sinus arrhythmia.

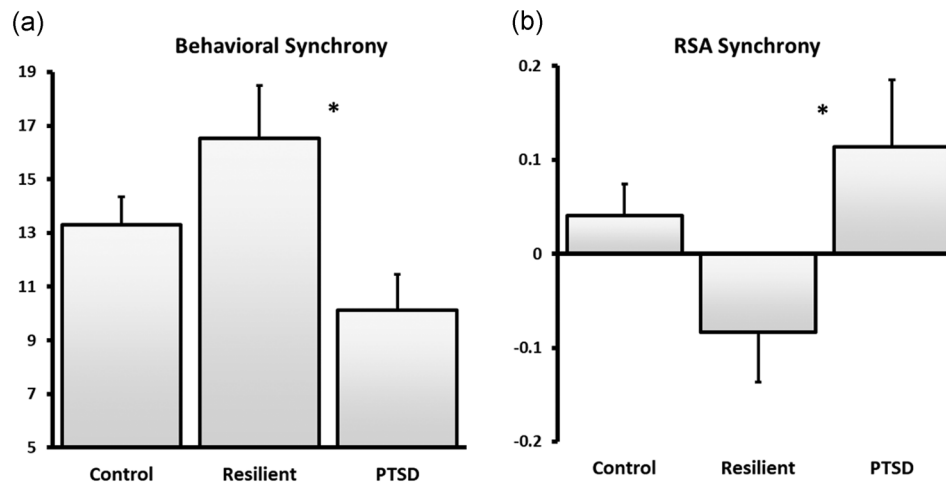


FIGURE 2 Group differences in behavioral synchrony and RSA synchrony levels during the social interaction task. (Mean ± SE). PTSD, posttraumatic stress disorder; RSA, respiratory sinus arrhythmia. * $p < .05$

with the PTSD group ($p = .044$) and no other group differences were found for other tasks ($p \geq .236$). ANOVA Analysis of baseline and attachment reminders tasks showed no significant group difference in RSA synchrony; $F_{2,89} = .293$, $p = .747$; $F_{2,82} = .530$, $p = .591$, respectively. Notably, RSA synchrony was not significantly associated with the mothers' or children's RSA levels or with RSA flexibility (i.e., variability) during the dyadic social-interaction task (p 's $> .215$).

3.2 | Mother-child behavioral synchrony

ANOVA for the interaction task using the averaged behavioral synchrony score showed significant group difference; $F_{2,90} = 4.204$, $p = .018$ (Figure 2). Post hoc comparisons showed higher behavioral synchrony in resilient, compared with PTSD dyads ($p = .014$), with no other differences ($p \geq .287$). These findings chart a complementary mechanism:

tighter RSA and lower behavioral synchrony in PTSD dyads, and greater behavioral and lower RSA synchrony in resilient dyads.

3.3 | Concordance of RSA and behavioral synchrony

The results of HLM analysis are reported in Table 2. As the table shows the moderation effect of group on the concordance of the dyad's RSA synchrony and behavioral synchrony approached significance. Follow-up simple slope analyses revealed that for resilient (Est. = -0.238 , SE = 0.111 , CI_{95%} = -0.456 to -0.020 , $p = .032$) and control (Est. = -0.193 , SE = 0.064 , CI_{95%} = -0.318 to -0.067 , $p = .003$) groups, behavioral synchrony linked with lower RSA synchrony. However, for PTSD dyads, behavioral synchrony did not attenuate RSA synchrony (Est. = 0.081 , SE = 0.117 , CI_{95%} = -0.148 to 0.309 , $p = .489$; Figure 3).

TABLE 2 Hierarchical Linear Model on the moderation effect of behavioral synchrony and group on mother-child RSA synchrony

| Fixed effects | Numerator DF | Denominator DF | F | p |
|---|--------------|----------------|-------|------|
| Intercept | 1 | 165.672 | 0.167 | .683 |
| Mother's RSA | 1 | 69.647 | 1.248 | .268 |
| Behavioral synchrony | 1 | 70.662 | 6.471 | .013 |
| Group | 2 | 165.537 | 0.088 | .916 |
| Mother's RSA × behavioral synchrony | 1 | 15,314.860 | 4.061 | .044 |
| Group × mother's RSA | 2 | 69.665 | 3.255 | .045 |
| Group × behavioral synchrony | 2 | 70.118 | 0.662 | .519 |
| Group × mother's RSA × behavioral synchrony | 2 | 15,271.164 | 2.495 | .083 |

Abbreviations: DF, degrees of freedom; RSA, respiratory sinus arrhythmia.

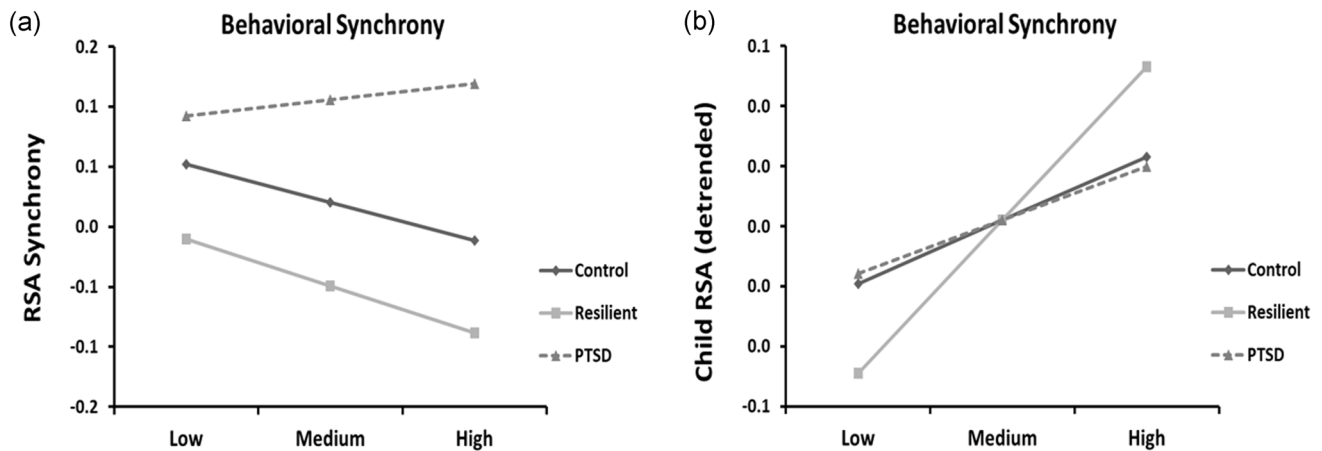


FIGURE 3 Dynamic second-by-second level behavioral synchrony in relation to dynamic mother-child RSA synchrony and child RSA levels. (a) Moments of behavioral synchrony are associated with lower mother-child RSA synchrony for the resilient and control groups but not for the PTSD group. (b) Moments of behavioral synchrony are associated by significantly higher child RSA levels compared with moments of nonsynchrony for the resilient group, but not for the PTSD and control groups. Note: Levels of behavioral synchrony are based on frequencies of behavioral synchrony for each moment. PTSD, posttraumatic stress disorder; RSA, respiratory sinus arrhythmia

To probe these results, we examined the association between behavioral synchrony and momentary RSA levels by computing additional HLM where child RSA was the outcome and behavioral synchrony the predictor. For the resilient group, moments of behavioral synchrony were characterized by higher child RSA levels; (Est. = 0.310, SE = 0.147, CI_{95%} = 0.017 to 0.602 $p = .038$). No such association emerged for the PTSD and control groups; (Est. = 0.108, SE = 0.154, CI_{95%} = -0.199 to 0.414, $p = .487$) and (Est. = 0.128, SE = 0.106, CI_{95%} = -0.085 to 0.340, $p = .235$), respectively (Figure 3). No association emerged between behavioral synchrony and mothers' RSA in any group; (Est. = -0.049, SE = 0.102, CI_{95%} = -0.253 to 0.156, $p = .635$, Est. = 0.001, SE = 0.109, CI_{95%} = -0.217 to 0.218 $p = .994$, and Est. = -0.027, SE = 0.073, CI_{95%} = -0.173 to 0.119, $p = .712$) for resilient, PTSD, and controls, respectively.

4 | DISCUSSION

With the shift in focus from psychopathology to resilience in the field of mental health (Feldman, 2020; Kalisch et al., 2019), there is a growing need to define specific, biologically based mechanisms that tilt children toward a resilient trajectory, examine these mechanisms in longitudinal studies, and tap the attachment relationship, which provides the main source of resilience in the face of trauma. The current study is the first to test a specific resilience-promoting, attachment-based mechanism—*biobehavioral synchrony*—at the transition to adolescence. We focused on the temporal interplay of physiological and behavioral synchrony, each of which shown to index healthy versus high-risk development (Feldman, 2015) and tested these two forms of synchrony as dual markers of risk and resilience among children exposed to chronic trauma since birth.

Overall, our findings demonstrate alterations in both behavioral and physiological synchrony as well as in their dynamic interplay in

youth exposed to chronic early trauma. Notably, differences in synchrony were observed during the social interaction, not during the baseline recording or during the viewing of attachment reminders, indicating that live social encounters provide an opportunity for online coordination of physiological and social signals that are sensitive to high-risk conditions. Our findings indicate that resilient children and their mothers exhibited greater behavioral synchrony and lower autonomic synchrony compared to youth exposed to similar war-related trauma who developed PTSD. Behavioral synchrony, the mother and child's online coordination of nonverbal signals, has been repeatedly shown to index well-being and adaptation in multiple high-risk populations (Feldman, 2007b, 2016). In the context of chronic trauma, behavioral synchrony predicts better functioning of the social brain in both child (Levy, Goldstein, et al., 2019) and mother (Levy, Yirmiya, et al., 2019). Synchrony tunes the child's brain to the social ecology and its hardships and provides repeated practice in the interplay between moments of interactive mismatch and reparation, thereby supporting resilience which involves plasticity, engaged sociality, and the capacity to recalibrate (Feldman, 2020).

Whereas mother-child RSA synchrony in early childhood typically predicts greater resilience (Gray et al., 2018; Lunkenheimer et al., 2015, 2018), the literature regarding RSA synchrony in early adolescence is mixed (Creavy et al., 2019). Very few studies of RSA synchrony examined children beyond early childhood, with none addressing the ongoing interplay between autonomic and social synchrony within a longitudinal design (Davis et al., 2018). Our findings are consistent with conceptual models on resilience, which propose that development should become a key factor in the conceptualization of resilience and that resilience research should focus on pinpointing age-specific biological markers of well-being and adaptation (Rutter, 2013).

Our results describe two mechanisms by which lower RSA synchrony combined with high behavioral synchrony may promote

resilience. First, mothers of PTSD children, who themselves reported greater PTSD symptoms, exhibited tighter physiological coupling compared with those of resilient children. Anxious mothers tend to display heightened alertness and tighter coupling with their child (Granat et al., 2017) and maternal anxiety often concurs with intrusive, over-controlling parenting that leads children to resonate with the mother's heightened arousal (Kaitz & Maytal, 2005). Possibly, PTSD children are more attuned to their mother's stress-related physiology and while tight physiological synchrony may be beneficial in infancy, when mother serves an external-regulatory function for the infant's immature physiological systems, the mother's inability to relax the child's physiological dependence may prevent the maturation of self-regulatory functions, particularly under conditions of chronic stress. High parental involvement indexes risk for PTSD following trauma in adolescence (Bokszczanin, 2008), suggesting that tighter parental control diminishes resilience at this stage. This may also provide a possible explanation for the lack of consistency between our findings and prior research showing lower RSA synchrony between mothers with a history of depression and their children after early childhood (Amole et al., 2017; Woody et al., 2016). As opposed to the intrusive parenting of anxious mothers, depressed mothers tend to form shorter mutual gaze and their children display more gaze aversion (Feldman, 2007a; Granat et al., 2017), hence the low physiological synchrony might represent a way to counter this deprivation. Yet, further studies that combine ongoing behavioral and RSA synchrony in multiple risk contexts are needed. Our findings are also consistent with research on dyadic synchrony in other physiological domains such as cortisol, which showed that greater physiological synchrony in later childhood is associated with greater physiological stress and lower behavioral reciprocity (Pratt et al., 2017). Another study found that the child's level of negative affect during adolescent-mother interactions was related to amplified cortisol synchrony (Papp et al., 2009) and studies in younger children found associations between cortisol synchrony with parental psychopathology and child negative emotionality (Merwin et al., 2017).

Results of the HLM analysis underscore not only the overall balance between physiological and behavioral synchrony but also their dynamic, in-the-moment interplay. Moments of social synchrony were linked online with the suppression of physiological synchrony only in the resilient and control groups, indicating that for these children the interpersonal exchange relied on the "loose" mechanisms of behavioral coordination rather than on the developmentally immature mechanism of physiological coupling. The parasympathetic system's regulatory function involves adaptive responses to momentary changes in individual-context conditions, and the data suggest that such mechanism may be practiced between mothers and resilient children during social moments. Mothers of resilient children appear to support the consolidation of the child's autonomic self-regulation by reducing the degree of physiological coupling but enhancing the coordinated framework of the relationship through increased behavioral synchrony.

The second dynamic mechanism was found only in the resilient group where moments of behavioral synchrony co-occurred with

increases in the child's RSA levels. Higher RSA has been repeatedly shown to index effective self-regulation and to support prosocial engagement and flexibility (Beauchaine, 2001; Porges, 2007). Parent-child interaction is arguably the primary context for the consolidation of RSA (Gray et al., 2017). Thus, mechanisms that differentiated the resilient and PTSD children, both exposed to similar chronic stressors, involved the capacity to maintain greater stretches of behavioral synchrony and the ability to increase parasympathetic activity during these moments. Considering the bidirectional nature of mother-child synchrony, the independent contribution of each partner may have induced a dyadic allostatic process that utilized moments of behavioral matching to decrease physiological arousal, thereby conserve energy. Such capacity may have enhanced the dyadic ability to repair moments of ruptures, which, in turn, may have augmented their behavioral synchrony. This notion is consistent with a recent study that addressed mother-child RSA synchrony in relation to rupture and repair processes and suggested that repair characteristics are related to dyadic allostatic processes. Furthermore, the high-risk context of maltreatment was found to modulate this association (Lunkenheimer et al., 2019).

During typical development, mother-infant interaction involves a delicate balance between unsynchronized moments combined with less frequent moments of synchrony to enable the development of child self-regulation (Tronick, 1989), indicating that rupture is essential for normal development but only in the context of a balanced repair. Our findings that suppression of parasympathetic synchrony is evident during moments of behavioral synchrony only in the resilient and control groups resonate with Tronick's view and expanded it into a multidimensional process. Our results suggest that behavioral synchrony serve as a special context in which ruptures, evident by suppression of allostatic synchrony, become not only tolerable and adaptive but resilience-promoting. Further research is required to directly tackle our perspective on dyadic allostasis and rupture-repair process for further insights on this issue.

The etiology and characterization of childhood PTSD requires much further research to detail factors that underpin individual variability following trauma. Significantly more research is needed to define processes that protect against the development of PTSD in the context of adversity. In addition to well-known psychosocial factors, such as contextual support, physiological determinants have been suggested as important predictors of resilience following trauma and as indicators of allostasis and regulation (Masten, 2007; Southwick et al., 2014); yet, no study has focused on the ongoing mutual influences of physiological and relational processes as they unfold in time as mechanisms of resilience. Prior research has shown that RSA synchrony during couple conflict is associated with increased inflammation and mother and child's immune biomarkers define risk and resilience following trauma (Ulmer-Yaniv et al., 2018; Yirmiya et al., 2018) and thus, future research may examine whether the interplay of RSA and behavioral synchrony impact PTSD and resilience through boosting or suppressing the immune system.

Several study limitations should be mentioned. First, although our study is prospective and longitudinal, no causal inferences can be

drawn. Second, unlike the repeated assessment of the child's psychiatric condition, RSA data were collected only at the final time-point, precluding our ability to chart the development of RSA in relation to parenting and symptomatology. Third, the lack of father data is a clear study limitation. Fourth, while all dyads in the exposed group were exposed to a similar type of trauma, potential heterogeneity may exist in terms of proximity or intensity to the traumatic events. Our study is the first to highlight the interplay of physiological and behavioral synchrony as markers of risk and resilience following trauma. As the number of children exposed to armed conflict world-wide is continuously on the rise and the availability of high-impact and far-reaching weapons places millions of children at risk, the need to pinpoint mechanisms that sustain resilience is paramount. Our results have implications for clinical practice and may be used to help mothers relax their tight coupling with the child and enhance behavioral attunement. Much future work is needed to tease apart mechanisms of resilience across ages; test a variety of biological, physiological, and neural systems that bolster resilience; and develop age- and condition-specific interventions that may chart possible pathways to resilience.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

Data can be obtained from the first author (shaimotsan@gmail.com) upon demand.

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