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Mother-infant physiological synchrony in the context of childbirth-related posttraumatic stress symptoms

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ABSTRACT

Synchrony in mother-infant interactions is crucial for infant development. However, mother-infant physiological synchrony in the context of maternal childbirth-related posttraumatic stress symptoms (CB-PTSS) remains unknown. This pilot study aimed to investigate physiological synchrony within the context of CB-PTSS. Additionally, it investigated the association between mother-infant physiological synchrony and reciprocity. A total of 86 French or English-speaking mothers and their term infants participated in the study. Maternal CB-PTSS was assessed using the PTSD Checklist for DSM-5 (PCL-5), modified for childbirth. Mother-infant dyads were classified into three groups based on their responses to the PCL-5. During mother-infant interactions, physiological synchrony was measured using heart rate variability (HRV), while reciprocity was observed in video recordings. Cross-lagged analysis revealed distinct patterns of HRV fluctuations between mother-infant dyads: positive (mother and infant HRV fluctuated in the same direction) or negative (mother and infant HRV fluctuated in the opposite direction). To avoid canceling out potential effects by averaging the positive and negative correlation coefficients, we analyzed them separately. In positive dyads, maternal HRV led infant HRV by approximately two seconds. Conversely, in negative dyads, there was no significant lag or lead observed in either direction. Our analysis did not reveal a significant impact of CB-PTSS group classification on the physiological synchrony between mothers and their infants. Additionally, we found no significant relation between physiological synchrony and reciprocity within the dyads. We recommend that future studies with a similar focus should control for factors such as individual physiological regulation, maternal anxiety, and maternal depression to further explain these relationships.

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1. Introduction

Mother-infant synchrony during interactions is identified as a protective factor in infant development because it facilitates better biological rhythms, improving infant vagal activity and enhancing infant self-regulation, and fostering attachment security, thus laying the foundation for healthy social and emotional development during the first years of life (Abney et al., 2021; Feldman, 2007a, 2012; Leblanc et al., 2017). Through behaviors such as mirroring each other's movements and expressions, mothers and infants engage in synchronized interactions that promote trust and an emotional connection that enhances communication and reduces stress (Beebe et al., 2010; Moore & Calkins, 2004). Thus, mother-infant synchrony is defined as joint and common navigation of moment-by-moment interactions between the mother and infant that involve two aspects: behavioral and physiological, where they coordinate their behaviors and physiological patterns in a smooth and on-line way, responding to each other's cues and signals (Provenzi et al., 2018). Physiological synchrony can be operationalized as the heart rhythms (Feldman et al., 2011; Nguyen et al., 2021). Meanwhile, mother-infant behavioral synchrony can be measured through emotional expressions, gaze, touch, vocalizations, and reciprocal adaptation (Leclere et al., 2014).

Heart rate variability (HRV) is an indicator to overall wellbeing, not only in adults but also in infants and often used as a measure of physiological synchrony (Kranjec et al., 2014; Oliveira et al., 2019). HRV is a biomarker of autonomic nervous system functioning that reflects vagal tone activity, which is known to be an indicator of emotion regulation functioning (Ahemaitijiang et al., 2021; Feldman et al., 2011; Smith et al., 2021). Lower HRV could be associated with mental health problems, including posttraumatic stress disorder (PTSD) (Benjamin et al., 2021; Hartmann et al., 2019; Tan et al., 2011). For example, mothers with depression showed lower HRV compared to healthy mothers (Hamilton & Alloy, 2016). These infants of mothers with higher stress levels or history of depression were also affected and had lower HRV compared to infants born to mothers without a history of depression and with less stress (Jacob et al., 2009).

Lower HRV in mothers may negatively affect their ability to physiologically synchronize with their infants (Suga et al., 2019). However, research on mother-infant physiological synchrony, particularly in vulnerable dyads, remains limited and shows mixed results. For example, a study by Woody et al. (2016) found that mothers with major depressive disorder (MDD) showed discordance in physiological synchrony with their infants compared to non-depressed dyads. In contrast, a study by Field et al. (1989) found no difference in physiological synchrony between mother-infant dyads with or without maternal depression.

These inconsistencies raise questions about whether maternal mental health issues disrupt physiological synchrony with infants. Furthermore, some studies suggest a potential bidirectional association between physiological and behavioral synchrony, where disruption in one may be linked to poorer coordination in the other (Davis et al., 2018; Woody et al., 2016). However, this potential association between physiological and behavioral synchrony still needs further investigation.

1.1. *Current study*

Following a traumatic childbirth experience, mothers may develop childbirth-related posttraumatic stress disorder (CB-PTSD), which has been proposed as a sub-type of PTSD (Horesh et al., 2021; Horsch et al., 2024). It consists of four symptom clusters: re-experiencing, avoidance, negative cognition and mood, and hyperarousal (American Psychiatric Association, 2022). When someone experiences these symptoms but does not meet all diagnostic criteria based on DSM-5, this is referred to as childbirth-related post-traumatic stress symptoms (CB-PTSS) (American Psychiatric Association, 2022; Ayers et al., 2023; Horesh et al., 2021). A recent meta-analysis showed a worldwide prevalence of CB-PTSS of 12.3 % (Heyne et al., 2022). Some research found that CB-PTSS may negatively impact mothers and infants, such as problems with bonding, poorer quality of the mother-infant interaction, and less optimal child development (Devita et al., 2024; Devita et al., 2023; Garthus-Niegel et al., 2017; Ionio & Di Blasio, 2014). Despite the high prevalence and negative outcomes, no studies have examined mother-infant physiological synchrony in the context of maternal CB-PTSS.

The primary aim of our pilot study was thus to investigate whether there is physiological synchrony between maternal and infant HRV during social interactions in the context of CB-PTSS at six months postpartum. Since CB-PTSS can be divided into birth-related symptoms (BRS, i.e., re-experiencing, avoidance) and general symptoms (GS, i.e., negative cognition and mood, hyperarousal) (Ayers et al., 2018; Sandoz et al., 2022), and recent research emphasizes the importance of examining symptom aspects separately rather than focusing only on the total score (as this can show different results since they may mask each other), we categorized CB-PTSS into three groups: non-symptomatic (NS), BRS, and GS. As explained above, given previous evidence that mental health problems may affect the dyad's physiological synchrony (Suga et al., 2019), we hypothesized that mother-infant HRV synchrony would be different between CB-PTSS groups: non-symptomatic (NS), BRS, and GS (hypothesis 1). Additionally, given the limited understanding in the literature regarding physiological and behavioral synchrony, our second aim was to explore the association between mother-infant physiological synchrony and reciprocity. Given the lack of evidence, no specific hypothesis was formulated for the second aim of this paper. As mentioned above, behavioral synchrony can be measured through reciprocal adaptation. We thus used reciprocity as an indicator for behavioral synchrony (Leclere et al., 2014).

2. Methods

2.1. *Study design and participants*

This is a cross-sectional, observational pilot study. Given that no study had yet investigated the mother-infant HRV synchrony in the context of CB-PTSS, the effect size could not be determined a priori. Comparable to studies investigating mother-infant HRV synchrony in a different context (Feldman et al., 2011; Field et al., 1989; Smith et al., 2021), we collected data from 86 mother-infant dyads. Data of 28 mother-infant dyads came from the control group of a randomised controlled trial on the prevention of CB-PTSS (NCT 03576586) (Sandoz et al., 2019). A further 58 dyads were recruited after that to have a large enough sample size. All data were collected at six months postpartum, as this time point aligns with previous research on mother-infant physiological synchrony (Abney et al., 2021; Suga et al., 2019). During this period, which typically ranges from three to nine months postpartum, infants begin to develop and engage more actively in social exchanges (Feldman, 2007a). We included French- and English-speaking mothers who gave birth to a living infant, at the gestational age of 37 weeks or more, and gave written consent. Exclusion criteria were no sufficient French or English language skills to participate, current psychotic illness, intellectual disability, severe illness of mothers or infants, alcohol abuse, or illegal drug use during pregnancy.

2.2. Procedure

The project was approved by the local cantonal ethics committee (2017–02142 and 2022–00716). Advertisement for the study was disseminated at maternity hospitals and through contact with daycare centers, gynecologists, and pediatricians. Furthermore, we posted the advertisement on the website of a Swiss university hospital and on social media platforms including Instagram, Facebook, and LinkedIn. After potential participants contacted us, we checked their eligibility and gave them further explanations about the research project, including the purpose of the study, the steps and procedures involved, risks and benefits of the study, the approximate duration of the study, and explained that study participation was voluntary. Mothers who agreed to participate then signed the informed consent form for their own participation and that of their infant.

At six months postpartum, participants were asked to complete online maternal self-report questionnaires (using the Research Electronic Data Capture (REDCap) software) (Harris et al., 2009). The questionnaire assessed maternal CB-PTSS, medical, and sociodemographic data. Within approximately one week of completing the online questionnaire, participants were invited to the observation lab at the university hospital, where their interactions were filmed in a room equipped with two movable cameras. Mothers were instructed to engage in a 15-minute free-play session with their infants, using a standardized set of toys provided by the researchers. There were no restrictions on movements during recording. They were allowed to move and position themselves freely, with the only guideline being not to obstruct the camera. For participants who had difficulties to come to the hospital for the appointment, home visits were arranged ($n = 43$). During these visits, the same procedure was followed, using the same set of toys but with only one camera, similar to previous studies in which researchers left the room during the interactions, and one research member periodically entered to ensure the mother-child remained in view of the camera (Kärtner & von Suchodoletz, 2021; Lindsey, 2022). Mothers were instructed to continue playing until directed to stop and to ignore the researcher who entered the room to check the camera during the interaction. HRV for both mothers and infants was recorded simultaneously during these interactions using a Firstbeat Bodyguard 2 device (Firstbeat Technologies, 2021).

2.3. Measures

2.3.1. Maternal CB-PTSS

Maternal CB-PTSS were measured with the PTSD Checklist for DSM-5, a 20-item self-report questionnaire assessing PTSS over the past month (Weathers et al., 2013), indicating childbirth as the index traumatic event. Participants responded using 0 (not at all) to 4 (extremely) Likert scale, with a higher score indicating more severe maternal PTSS (Weathers et al., 2013). The French version of the PCL-5 showed strong validity (Ashbaugh et al., 2016).

Mother-infant dyads were divided into three groups based on the maternal responses on the PCL-5. Re-experiencing and avoidance together were classified as BRS, e.g., repeated, disturbing, and unwanted memories of the recent childbirth. Meanwhile, negative cognition and mood, and hyperarousal were classified as GS, e.g., loss of interest in activities that the mother used to enjoy (Ayers et al., 2018; Sandoz et al., 2022). According to DSM-5, symptoms are counted when they are present as a score of 2 or higher (American Psychiatric Association, 2022). If the mother had a score of 2 or higher on BRS-related items (referring to items 1 through 8 and 10–11) (Weathers et al., 2013), she was assigned to the BRS group. If the mother had a score of 2 or higher for GS-related items (composed of items 9 and 12 through 20) (Weathers et al., 2013), she was assigned to the GS group. If none of the items was scored as 2 or higher, the mother was classified as belonging to the NS group. If a mother's total score on the items corresponding to BRS and GS were the same, she was assigned to the BRS group because one study found that items corresponding to BRS (compared to GS) had a greater impact on infant outcomes (Garthus-Niegel et al., 2017). In the present pilot study, the PCL-5 total showed a good internal consistency for both its total scale ($\alpha = 0.89$ [0.831, 0.922]) and its subscales (GS: $\alpha = 0.838$ [0.764, 0.88], BRS: $\alpha = 0.85$ [0.734, 0.899]).

2.3.2. Physiological synchrony

HRV, as an indicated variable for physiological regulation, was measured using the Firstbeat Bodyguard 2 (Firstbeat Technologies, 2021). As an ECG device, Firstbeat Bodyguard 2 records the heart's electrical activity during use. After recording, we transferred the ECG data directly to a computer by plugging the Firstbeat device in as a USB drive. The data was then stored on the Firstbeat cloud platform, from which we downloaded the HRV information. The Firstbeat Bodyguard 2 was attached to the mother's and infant's chest by two disposible electrodes. Maternal and infant HRV were measured during a 15-minute free-play session, with the mid-sequence (from minute three to minute six) selected for further analysis. This three-minute time frame has been used in previous studies (Abney et al., 2021; Feldman et al., 2011), and we chose this central segment for analysis to exclude the initial warm-up period of the interaction. The same three-minute window was used to analyse reciprocity.

2.3.3. Reciprocity

Behavioral synchrony was operationalized using the reciprocity subscale of the Global Rating Scales (Murray & Karpf, 2000), which defines reciprocity as the mutual exchange and coordination of actions between mother and infant. In this context, each responds to the other's input, demonstrating joint orientation, turn-taking, and shared involvement during free-play. This was scored as a macro analysis over an entire three-minute observation period, similar to physiological synchrony, based on filmed free-play interaction. Reciprocity was coded independently by three trained coders using a Likert scale from 1 (no reciprocity) to 5 (very much reciprocity), with an interrater reliability score of ≥ 0.79, indicating good interrater reliability.

2.3.4. Medical and sociodemographic data

Medical and sociodemographic data were collected through a maternal self-report questionnaire that included information on mother's age, marital status, nationality, education, parity, mode of childbirth, infant sex, gestational age, infant birthweight, and APGAR score at five minutes.

2.4. Statistical analyses

HRV signals recorded with Firstbeat devices were downloaded from the Firstbeat cloud and first pre-processed with Kubios application. The Kubios HRV analysis results were exported as Excel files to the R programming environment for further analysis. The dyads' HRV raw signals measured during the three minutes' interaction (minute three to minute six) were resampled into one second window timeframes using HRV values average or interpolation when appropriate. This ensured an even number of measures between the mother and the infant of the same dyad.

Outliers were identified as values greater than/less than the median ± the median absolute deviation. Dyad HRV signals with more than 30 % outliers and/or dyads having large series of consecutive similar values (i.e., more than 40 % of the measures) were excluded from the analyses. For the remaining dyads, outliers HRV signals were winsorized (i.e., replaced by maximum and minimum values calculated as the median ± the median absolute deviation). Thus, out of the 86 dyads in scope, 6 dyad HRV signals (1 dyad with more than 30 % of outliers, 5 dyads with more than 40 % of consecutive similar values) were excluded from the analyses. In total, the final analyses included 80 dyads, classified into NS (29 dyads), BRS (14 dyads), and GS (37 dyads) based on maternal self-report of PCL-5.

To test the physiological synchrony between mothers and infants (hypothesis 1), we followed these steps:

1. **Stationarity Assessment**: We conducted Phillips-Perron (PP) tests to assess the stationarity of the mother and infant HRV signals.
2. **Lag Structure Identification**: We identified the appropriate lag structure for the cross-lagged correlation analysis by comparing different Vector Autoregressive (VAR) models and selecting the optimal number of lags based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) information criteria.
3. **Cross-Lagged Correlations**: At the dyad level, we used cross-lagged correlations to check for any temporal patterns across positively and negatively cross-correlated dyads. For positive (mother and infant HRV were fluctuating in the same direction) and negative (mother and infant HRV were fluctuating in the opposite direction) cross-correlated dyads, we estimated temporal effects by calculating regression coefficients (Abney et al., 2021; Suveg et al., 2019). As averaging positive and negative correlation coefficients would have cancelled out the resulting distribution and, consequently, hidden some potential effects, we took the decision to treat the positively (34 dyads) and negatively (46 dyads) correlated dyads separately, similar to Abney et al. (2021). To minimize autocorrelations, we approximated the dyads' HRV signals with Autoregressive Integrated Moving Average (ARIMA) models with one autoregressive and one moving average term (Dean & Dunsmuir, 2016; Feldman et al., 2011). Cross-lagged correlations (with no time-lag) were computed for each dyad on ARIMA residuals. Positive and negative distributions were compared and differentiated from a null hypothesis of an average 0 correlation using Kolmogorov-Smirnov tests.
4. **Real vs. Surrogate Dyads Comparison**: We compared the HRV signals' cross-correlation (no time-lag) distributions between real and surrogate dyads (Feldman et al., 2011). The surrogate dyads were created by combining the HRV signals of a mother from one dyad with a randomly chosen infant of another dyad. Surrogate dyad cross-lagged correlation were calculated using a boosting strategy: for a given dyad, the cross-lagged correlation of the real dyad mother was computed with N infants of other dyads (sampling with replacement) and averaged. Kolmogorv-Smirnov tests were used to confirm that the mother-infant real dyads' cross-correlations distributions were not due to chance.
5. **CB-PTSS Groups Comparison**: Differences in mother-infant physiological synchrony between CB-PTSS groups were tested using ANOVA type III and pairwise tests on estimated marginal means with Tukey corrections to account for the unbalanced design of the CB-PTSS groups.

Finally, we fitted a linear model to examine the relationship between the mother-infant physiological synchrony and reciprocity, including the grouping variable CB-PTSS groups as both a main effect and in interaction with physiological regulation. The effect sizes were estimated following the guidelines provided by Orth et al. (2024) for interpreting the size of cross-lagged effects in longitudinal data. The statistical power estimates were based on a simulation-based approach using 10000 bootstrap samples with replacement for the Kolmogorov-Smirnov test, and Cohen's f and the F statistic for the ANOVA tests. Cohen's f effect size was considered small when $f \geq .10$, medium when $f \geq .25$, and large when $f \geq .40$ (Cohen, 1988).

The null hypothesis of the Kolmogorov-Smirnov test statistic (based on the maximum difference between the empirical cumulative distribution functions of the two samples) postulated that the distribution of dyad HRV correlations at lag 0 was equivalent to a distribution with an average correlation of 0. Alternatively, it suggested that the distribution of positive dyads was identical to the distribution of negative dyads. All the analyses were done using R v4.3.0 running in RStudio v2023.06.0 build 421 (R Core Team, 2023; RStudio Team, 2020). We used two-tailed significance, and $\alpha < .05$ for all statistical tests.

3. Results

3.1. Descriptive statistics

The mean age of mothers was 33.45 years (SD = 4.15). The majority were married, cohabitating, or in relationships (84.71 %, n = 72), and 65.88 % (n = 56) were Swiss nationals. Additionally, 68.60 % (n = 59) were primipara, and 76.47 % (n = 65) had received university or applied science education. Regarding childbirth, half of the mothers (48.84 %, n = 42) had vaginal births. Furthermore, 51.16 % (n = 44) of the infants were female. The median maternal PCL-5 score was 7 (IQR=10). The median gestational week was 40 (IQR=2), with median APGAR score 10 (IQR=1), mean infants' weight of 3373.95 g (SD=478.24).

Fig. 6a and 6b showed the stationarity of the HRV mother and infant distributions, which was evaluated using Phillips-Perron (PP) tests. For the mother HRV signal, the PP test value of −5.07 was less than the critical value at the 1 % significance level (-3.46), and we concluded that the mother HRV signals was stationary. For the infant HRV signal, the PP test (-3.40) was greater than the critical value at the 1 % significance level (-3.46) but less than the critical values at the 5 % (-2.88) significance level, suggesting there was sufficient evidence to conclude that the time series was stationary at the 5 % significance level.

The optimal lag length was determined for each dyad individually. For each dyad, a VAR model was fitted to the data with lag lengths ranging from 1 to 20 to determine the optimal lag length, using AIC and BIC criterion. The maximum (i.e, 6) of the optimal lag lengths distribution across dyads was selected to proceed with the cross-lagged correlation analysis of the mother and infant HRV signals. This value was consistent with the other dyads synchrony related studies using HRV (Provenzi et al., 2018) and aligned with the fact that HRV signals reflect autonomic nervous system activity, which typically operates on a relatively short time scale. The descriptive statics of the physiological regulation measured by the cross-correlation of the ARIMA residuals at time-lag 0 and the behavioural regulation measured by the reciprocity subscale of the Global Rating Scales are provided in Table 1.

3.2. Mother-infant physiological synchrony (hypothesis 1)

The cross-lagged correlation coefficients' distribution (Fig. 1), calculated as the mean of the cross-lagged correlation coefficients for all dyads at each time-lag shows a correlation optimum for the positively and negatively correlated dyads, suggesting a synchrony between the mother and her infant HRV signals. The positively correlated dyads showed a maximum correlation (r = 0.157 [-0.191, 0.470], p = .360) at a time-lag of 2 seconds, indicating that, on average, the mothers' HRV signals led the infants' HRV signal by 2 seconds, although this was not statistically significant. The negatively correlated dyads showed a minimum correlation (r = -0.147 [-0.419, 0.150], p = .393) at a time-lag of 0 seconds, indicating that, on average, neither the mothers', nor the infants' HRV signals were leading or lagging. These results were not statistically significant either. The effect sizes (r = 0.157, r = -0.147) could be considered low, as well as the related statistical power (0.144 for positive dyads, 0.164 for negative dyads). Post-hoc analysis showed

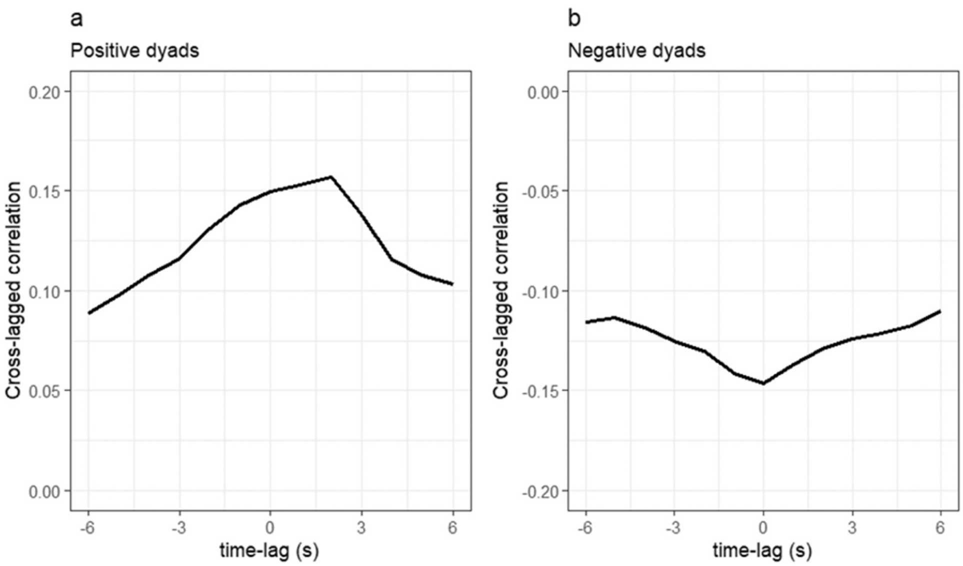

Fig. 1. Cross-lagged correlation coefficients' distribution. Positive time-lags: mother is leading, negative time-lags: infant is leading.

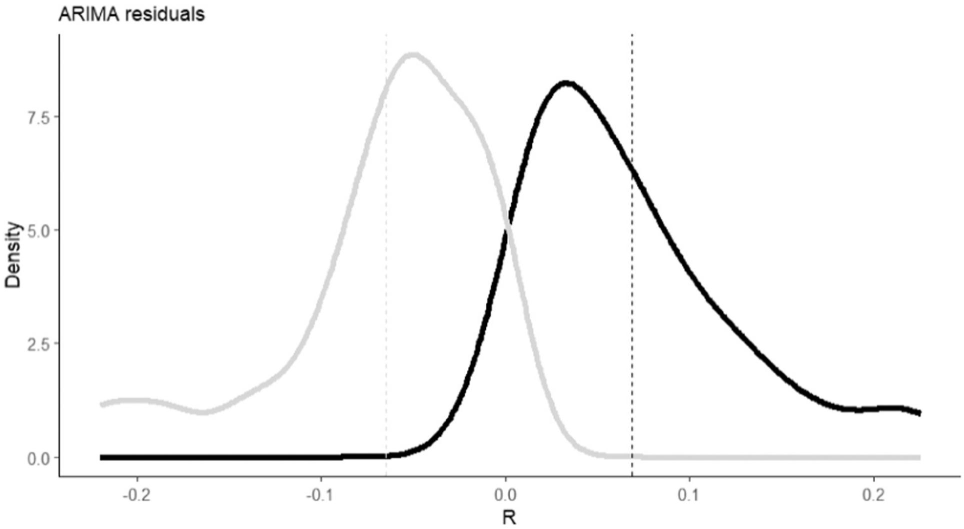

Fig. 2. ARIMA residuals cross-lagged correlation coefficients' distributions. Black line: positive distribution, light grey line: negative distribution; vertical dotted lines: distribution means; R: cross-lagged correlation; Density: kernel density estimate (smoothed version of histogram).

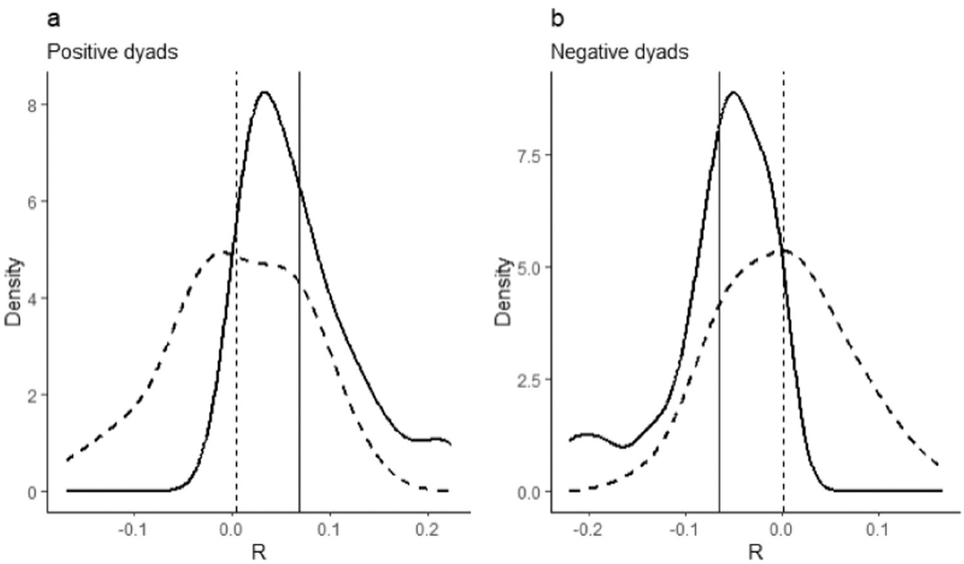

Fig. 3. Empirical vs surrogate distributions of positive and negative dyads. Surrogate distribution in dashed line, empirical distribution in solid line; vertical dotted lines: distribution means; R: cross-lagged correlation; Density: kernel density estimate (smoothed version of histogram).

that to reach a statistical power of 0.80 with the effect size observed, a sample size of 320 for the positive dyads and 360 for the negative dyads would have been required.

Fig. 2 shows the elimination of the effects of the auto-correlated part of each signal. This was achieved by fitting the dyads' HRV signals with ARIMA models, with one autoregressive term and one moving average term, and using the residual parts to compare the distributions of cross-correlation coefficients at time-lag 0 between positive and negative dyads. Kolmogorov-Smirnov tests showed that the distributions of the positive and negative ARIMA residuals cross-lagged correlation coefficients were significantly different ($D = 1$, $p < .001$) and also significantly different from a null hypothesis of an average correlation of 0 for both the positive dyads ($D = 0.50$, $p < .001$) and negative dyads ($D = 0.50$, $p < .001$). The statistical power estimates, based on the D statistic as the effect size and a bootstraping approach, were all greater than 0.95.

In the second set of analyses, we conducted a surrogate test to determine whether the cross-correlation coefficients from empirical dyads were statistically similar or different to those from random pairings of individuals into dyads (Feldman et al., 2011). To answer this question, for the positive and negative dyads' groups, separately, we randomly paired an infant from one dyad with a mother from another dyad and estimated the time-lag 0 cross-correlation coefficient. The results (Figs. 3a and 3b) showed that the surrogate

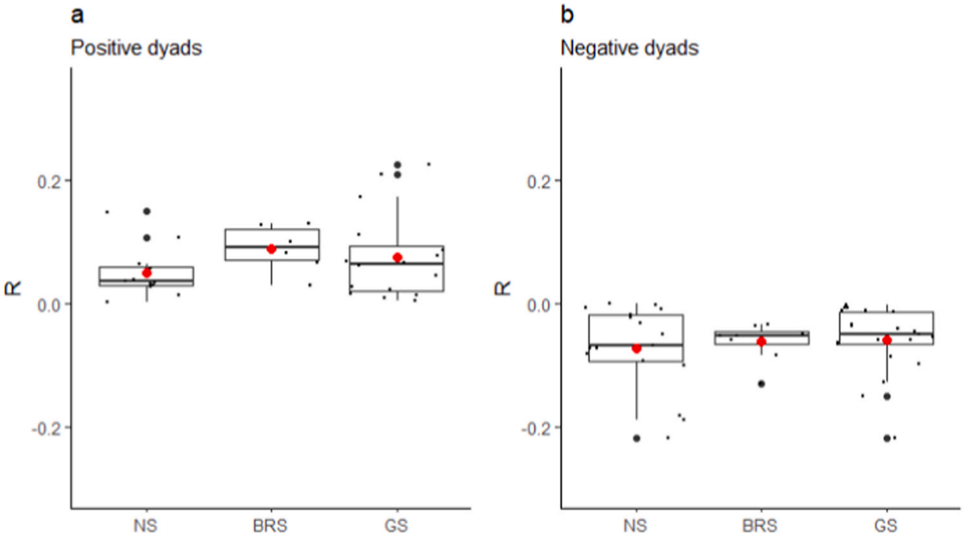

Fig. 4. ARIMA residuals cross-lagged correlation coefficients distributions per CB-PTSS classification. NS: non-symptomatic; BRS: birth-related symptoms; GS: general symptoms; the distribution estimated marginal means are represented by red dots, the medians by horizontal solid lines.

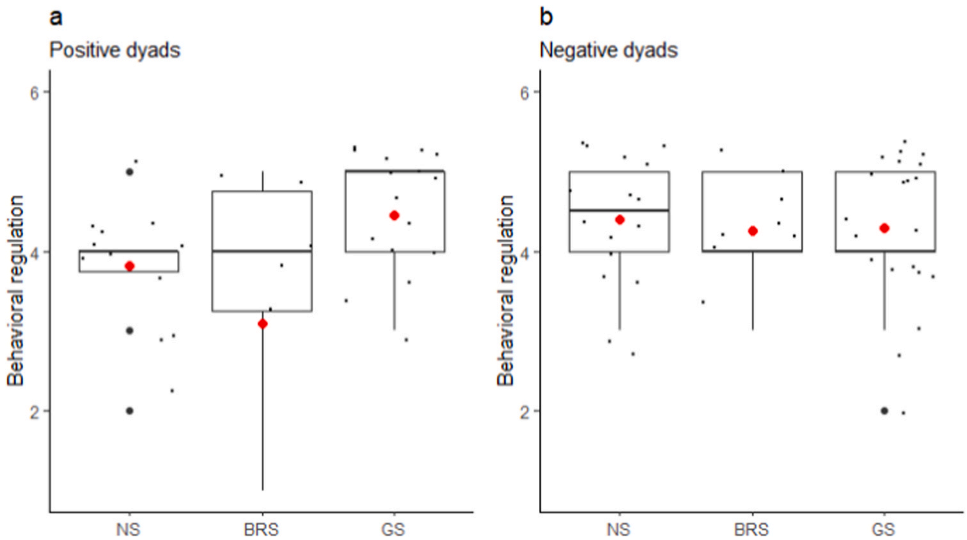

Fig. 5. Group comparison of the reciprocity - HRV coordination relationship. NS: non-symptomatic; BRS: birth-related symptoms; GS: general symptoms; the distribution estimated marginal means are represented by red dots, the medians by horizontal solid lines.

distribution was centered at 0, as expected, indicating no correlation. The Kolmogorov-Smirnov tests revealed that empirical and surrogate distributions were not sampled from the same population for the positive dyads ($D = 0.50$, $p < .001$) nor the negative dyads ($D = 0.50$, $p < .001$), confirming that the mother-infant empirical dyads' cross-correlations' distributions were not drawn from chance. The statistical power estimates, based on a bootstrapping approach, were greater than 0.95 for both positive and negative dyads.

Finaly we tested the mean difference of ARIMA residuals cross-lagged correlation coefficients per CB-PTSS groups using Type III ANOVA models. The results showed that, for the positive dyads (Fig. 4a), there were no significant differences in mean physiological regulation between the CB-PTSS groups ($F(2, 31) = 1.220$, $p = .308$). A power analysis was conducted to determine the ability of the statistical test to detect differences between the CB-PTSS groups. Although the effect size was considered medium ($f = 0.281$), the statistical power estimate for each was low (NS: 0.282, BRS: 0.148, GS: 0.372) and could be attributed to the small sample sizes in this pilot study (NS =12, BRS = 6, GS = 16). For the negative dyads (Fig. 4b), there were no significant differences in mean physiological regulation between the CB-PTSS groups either ($F(2, 43) = 0.240$, $p = .788$). The effect size was considered low ($f = 0.106$), as well as the corresponding statistical power estimates (NS: 0.093, BRS: 0.068, GS: 0.104) due to the small sample sizes (NS = 17, BRS = 8, GS = 21). A post-hoc power analysis was conducted to determine the sample sizes required in three groups to achieve a statistical power of at

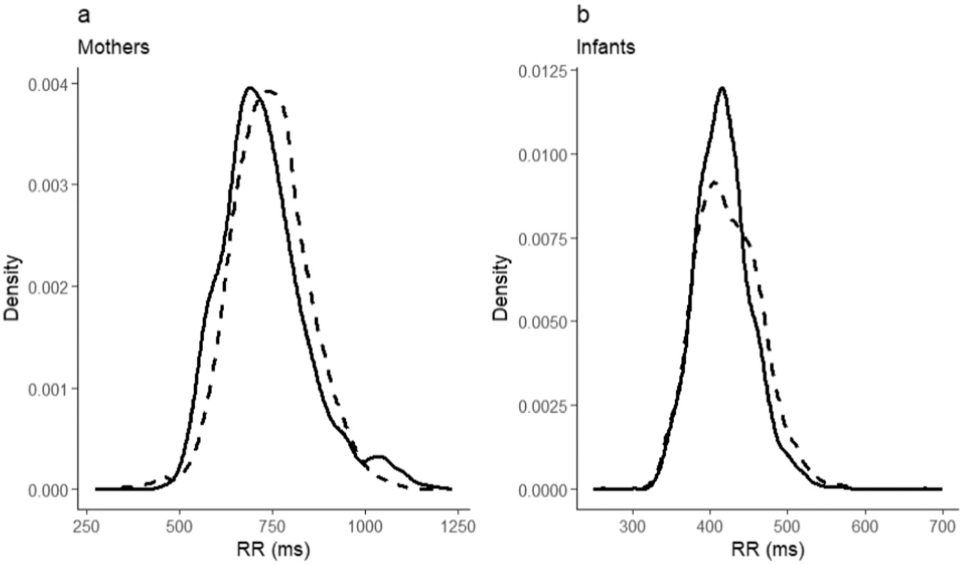

Fig. 6. Dyads RR distribution. Solid line: positive dyads, dashed line: negative line; Density: kernel density estimate (smoothed version of histogram).

Table 1
Physiological regulation and dyads' reciprocity: descriptive statistics.

CB-PTSS group	Positive Dyads			Negative Dyads		
	N	Phys. Reg.[a] Mean (sdt.dev.)	Reciprocity[b] Mean (sdt.dev.)	N	Phy. Reg.[a] Mean (sdt.dev.)	Reciprocity[b] Mean (sdt.dev.)
Total	34	0.069 (0.057)	4.059 (0.952)	46	−0.065 (0.056)	4.311 (0.763)
NS	12	0.049 (0.041)	3.75 (0.754)	17	−0.072 (0.068)	4.375 (0.719)
GS	16	0.076 (0.07)	4.438 (0.727)	21	−0.059 (0.054)	4.286 (0.845)
BRS	6	0.089 (0.039)	3.667 (1.506)	8	−0.063 (0.031)	4.25 (0.707)

[a] Physiological regulation measured by the cross-correlation of the ARIMA residuals at time-lag 0;
[b] Reciprocity measured by Global Rating Scales; BRS (birth-related symptoms); GS (general symptoms); NS (non-symptomatic)

least 0.80. The analysis was performed using a simulation-based approach based on the observed between-group and within-group variances from the initial data, taking into account the unbalanced design of the study. For the positive dyads, the results indicated that the following sample sizes (NS = 1212, BRS = 1206, GS = 1216) were needed to achieve a power of approximately 0.80. For the negative dyads, the sample size required were (NS = 1217, BRS = 1208, GS = 1221).

To address concerns related to the small sample size of the CB-PTSS groups, a post-hoc analysis was conducted to investigate the relationship between mother-infant synchrony operationalized as optimum raw cross-lagged HRV correlations for positive and negative dyads and the maternal CB-PTSS, measured as a continuous total score. The results (Table 2, Fig. 7) revealed a significant effect of the CB-PTSS total score for the positive dyads (β=-0.005, p = .028), i.e., the higher the CB-PTSS, the lower the raw cross-lagged correlations. No such significant effect was found for the negative dyads (β=0.002, p = .136). The effect sizes were considered small (R2 =0.142 and R2 =0.05 respectively).

3.3. *Mother-infant physiological synchrony and reciprocity*

For the positive dyads, we found no significant main effect of the HRV synchrony (physiological synchrony) on reciprocity (F(1, 28) = 0.380, p = .542). The effect size and corresponding statistical power were considered small (f = 0.111 with a power of 0.09). We found a significant main effect of the CB-PTSS groups (Fig. 5a) on reciprocity (F(2, 28) = 6.500, p = .005). The effect size (f = 0.400) was considered medium to large, and the statistical power medium (power = 0.56) due to the small sample size. The interactions between the CB-PTSS group and the HRV were also significant (F(2, 28) = 4.01, p = .03). The related effect size (f = 0.48) was considered large and the statistical power (0.720) medium. The estimated marginal mean, for reciprocity was significantly higher for the GS group compared to the BRS group (estimated marginal mean difference = 1.341, p = .015) but not significantly higher compared to the NS group (estimated marginal mean difference = 0.622, p = .182). There were no significant difference in reciprocity between the BRS and NS group (estimated marginal mean difference = −0.720, p = .304). A power analysis was conducted to determine the sample sizes required to achieve a statistical power of at least 0.80. For the positive dyads, the results indicated that the following sample sizes (N = 638 for the main effect of HRV synchrony, N = 52 for the main effect of the CB-PTSS groups and N = 46

Table 2
Dyads' physiological regulation and maternal CB-PTSS.

Dyad Valence	N	Var	Estimate	t value	Pr(>|t|)	R^2	Power	Sample size
Positive	34	Total score	−0.005	−2.303	0.028 *	0.142	0.608	50
Negative	46	Total score	0.002	1.519	0.136	0.05	0.318	152

Notes: Sample size is the sample size that would be required to reach a statistical power of 0.80; GS is General Symptoms; BRS is Birth Related Symptoms

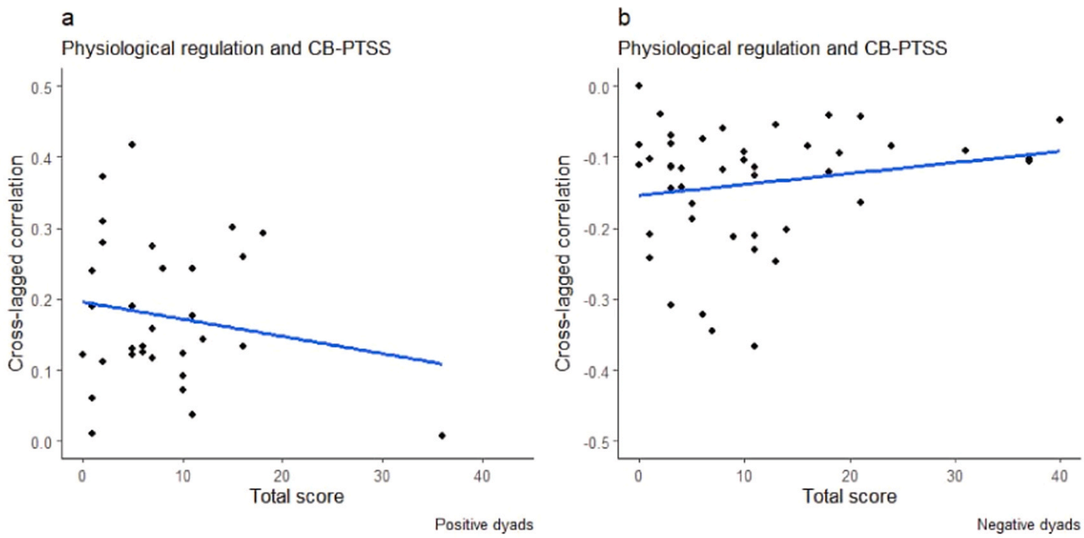

Fig. 7. Physiological regulation and maternal CB-PTSS.

for their interaction) were needed to achieve a power of approximately 0.80.

For the negative dyads, we found no significant main effect of HRV synchrony on reciprocity (F(1, 39) = 0.293, p = .591), with an effect size and corresponding statistical power considered small (f = 0.043 with a statistical power of 0.056). We did not find a significant main effect of the CB-PTSS groups (Fig. 5b) on reciprocity either (F(2, 39) = 0.204, p = .820), with an effect size and statistical power considered small (f = 0.070 with a statistical power of 0.066). The interactions between the CB-PTSS group and the HRV were not significant (F(2, 39) = 0.139, p = .870). The effect size and statistical power were considered small (f = 0.084 with a statistical power of 0.073). For the negative dyads, the sample size required were (N = 4339 for the main effect of HRV synchrony, N = 1607 for the main effect of the CB-PTSS groups and N = 1362 for their interaction) to achieve a power of approximately 0.80.

4. Discussion

This observational pilot study aimed to firstly explore the synchrony between the mother and infant physiological regulation during free-play interactions at six months postpartum, in the context of CB-PTSS. Consistent with the findings of Feldman et al. (2011), the results hint at a possible temporal relationship in HRV signals for positive dyads, which could be explored further in future studies with larger sample sizes to achieve statistical significance. However, in our pilot study, we found that in positive dyads, maternal HRV signals led infant HRV signals without reciprocal influence where infant HRV did not lead maternal HRV, which is different from Feldman et al. (2011) who reported bidirectional influences, where changes in infant HRV corresponded to changes in maternal HRV and vice versa. Maybe this is because Feldman et al. (2011) explored the physiological synchrony in the context of healthy dyads. For negative dyads, the results suggest a lack of temporal relationship in HRV signals, which could indicate different dynamics in the mother-infant interaction. This also raises questions about the factors that might influence the presence or absence of such synchrony, such as the emotional or behavioral state of the dyads (Capraz et al., 2023). Future research could benefit from taking into account these factors or combining our statistical approach with other analytical techniques to gain deeper insights about the temporal dynamic of mother-infant dyads. The simple interaction play used in this study involving natural, unstructured interactions between the mother and infant, and allowing for the observation of spontaneous behaviors and physiological responses could be seen as restrictive. Other methods like the still-face interaction allowing researchers to observe the infant's reaction to the sudden loss of social engagement and their ability to recover when the interaction is resumed would be more efficient to elicit a mild stress response in the infant (Messerli-Bürgy et al., 2025), which can be useful for studying the regulation of emotions and the role of the caregiver in buffering stress. In the context of HRV, it can reveal how the infant's autonomic nervous system responds to social stress and recovery.

Moreover, we did not observe differences in physiological synchrony between the CB-PTSS groups (BRS, GS, and NS). This suggests that these symptoms may not be severe enough to significantly affect physiological synchrony, or alternatively, the effect may not have been detected due to our small sample size in this pilot study, which is addressed as our main limitation. Nevertheless, our results align with those from a study by Field et al. (1989), which found no significant differences in physiological synchrony between mother-infant dyads with and without maternal depression symptoms. Although Field et al. (1989) examined maternal depression symptoms rather than CB-PTSS, it similarly suggests that milder symptoms may not have a substantial effect on physiological synchrony. In contrast, studies focusing on more severe maternal mental health conditions, like maternal history of MDD, have found differences in physiological synchrony (Amole et al., 2017; Woody et al., 2016). For example, Woody et al. (2016) found less physiological synchrony between school-age children and their mothers who had a history of MDD. Similarly, Amole et al. (2017) reported that physiological synchrony was affected in adolescents whose mothers had an MDD, suggesting the more severe and chronic nature of MDD may lead to greater disruptions in maternal-infant physiological synchrony. Moreover, the discrepancies in findings may be related to the different developmental stages of children. The study by Field et al. (1989) involved infants aged around three months, which, although different from our study (with infants at six months old), is still comparable. In contrast, the study by Woody et al. (2016) included much older children, aged seven to eleven years, and a study by Amole et al. (2017) that included adolescents. We observed no significant association between physiological and reciprocity in the general context of CB-PTSS. This findings contradict the results by Feldman et al. (2011) who observed when mother-infant dyads engaged in synchronized or reciprocal behaviors, such as through vocalizations and emotional expressions, their heart rhythms also synchronized significantly. Several potential explanations may account for the absence of significant results in our study. First, unlike the study by Feldman et al. (2011), we did not observe reciprocity as a time series but instead coded it on a Likert scale as a macro-level measure. This approach might have prevented us from identifying the dynamic, real-time relationship between mother and infant physiological and reciprocity during interactions. However, our study aligned with results by Field et al. (1989) who found no association between behavioral and physiological synchrony, even though they used time series measures for the behavioral synchrony. Thus, perhaps a further explanation may be the fact that we did not include measures of positive affect in the interaction between mother and infant, which has been shown to play a crucial role in moderating the relationship between behavioral and physiological synchrony (Capraz et al., 2023). When positive affect is present, dyads are more likely to align their physiological synchrony and reciprocity within the dyad (Capraz et al., 2023). This might explain why Feldman et al. (2011) who focused on healthy dyads, found associations between physiological synchrony and reciprocity, because these dyads likely displayed more positive affect compared to our study and findings by Field et al. (1989). Another study also highlighted the importance of understanding the nuance of the interaction is crucial in interpreting the synchrony (Smith et al., 2021). That study showed that when stress in dyads was high, mothers with lower anxiety tended to desynchronize their behavior (measured with micro-analysis) to help regulate the dyad, while physiological synchrony remained unchanged. In contrast, dyads with more anxious mothers exhibited higher physiological synchrony, possibly reflecting maladaptive co-regulation (Smith et al., 2021).

Therefore, for future research, it is recommended to include the measure of mother and infant positive affect to know the nuances and context of the interaction. Additionally, future studies may incorporate time-series measurements for reciprocity or behavioral synchrony to confirm our findings and explore the underlying mechanisms of the association, or lack thereof, between physiological and behavioral synchrony in the context of CB-PTSS. Moreover, exploring different procedures could help determine whether varying experimental conditions produce different or consistent results. In our study, mothers were instructed to engage with their infants as they typically would at home. If infants are positioned in a chair that restricts physical contact with their caregiver, such as in an upright position, there may be a reduced opportunity for tactile cues that typically enhance responsiveness and coordination of interactions (Feldman, 2007b).

In conclusion, this innovative pilot study is the first to explore mother-infant physiological synchrony (HRV) and its association with reciprocity in the context of maternal CB-PTSS during free-play interactions, addressing a significant gap in the literature and advancing the understanding of mother-infant synchrony in CB-PTSS. In addition, we applied comprehensive extensive analysis techniques to confirm our findings. While our study provides novel insights, it has limitations. As a pilot study, our sample size was relatively small, therefore, the results need to be interpreted with caution. The post hoc analysis of the total maternal CB-PTSS score and mother-infant physiological synchrony provided some insights, but the results should be interpreted with caution due to the low statistical power of the study. The cross-sectional design did not allow us to understand the changes of this association between maternal CB-PTSS and mother-infant HRV and reciprocity over time. The generalizability of our findings is limited to mother-infant dyads with term infants. In addition, the lacking association between physiological synchrony and reciprocity might have been biased due to individual differences in the capacity for physiological regulation, such as vagal suppression that interacts with dyads' reciprocity (Abney et al., 2021; Busuito et al., 2019). Further studies with the recommended sample size mentioned in our post-hoc analysis are needed to confirm our findings while controlling for possible covariates, including individual differences in the capacity of physiological regulation, dyads affect during interaction, maternal anxiety, and maternal depression (Abney et al., 2021; Capraz et al., 2023; Field et al., 1989; Smith et al., 2021).

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CRediT authorship contribution statement

Devita Sella: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Messerli-Bürgy Nadine:** Writing – review & editing, Resources, Methodology, Conceptualization. **Lacroix Alain:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Deforges Camille:** Writing – review & editing, Investigation. **Bozicevic Laura:** Writing – review & editing, Investigation. **Rattaz Valentine:** Writing – review & editing. **Tolsa Jean-François:** Writing – review & editing, Supervision. **Sandoz Vania:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Horsch Antje:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Conflict of Interest

The authors declared no potential conflicts of interest. Antje Horsch is on the management board of COST Action 22114.

Data Availability

Data will be made available on request.

References

Abney, D. H., daSilva, E. B., & Bertenthal, B. I. (2021). Associations between infant–mother physiological synchrony and 4- and 6-month-old infants' emotion regulation. *Developmental Psychobiology, 63*(6). https://doi.org/10.1002/dev.22161

Ahemaitijiang, N., Ren, H., Wang, H., & Han, Z. R. (2021). Longitudinal association between emotion-related parenting behavior and child aggression: The moderating role of parent-child physiological synchrony. *Aggressive Behavior, 47*. https://doi.org/10.1002/ab.21945

American Psychiatric Association. (2022). *Diagnostic and Statistical Manual Of Mental Disorders: DSM-5-TR*. American Psychiatric Association Publishing.

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

Ashbaugh, A. R., Houle-Johnson, S., Herbert, C., El-Hage, W., & Brunet, A. (2016). Psychometric validation of the english and french versions of the posttraumatic stress disorder checklist for DSM-5 (PCL-5). *PLOS ONE, 11*(10). https://doi.org/10.1371/journal.pone.0161645

Ayers, S., Horsch, A., Garthus-Niegel, S., Nieuwenhuijze, M., Bogaerts, A., Hartmann, K., Karlsdottir, S. I., Oosterman, M., Tecirli, G., Turner, J. D., & Lalor, J. (2023). Traumatic birth and childbirth-related post-traumatic stress disorder: Recommendations for practice, policy, and research. *Women and Birth*. https://doi.org/10.1016/j.wombi.2023.11.006

Ayers, S., Wright, D. B., & Thornton, A. (2018). Development of a measure of postpartum PTSD: the city birth trauma scale. *Frontiers in Psychiatry, 9*, 409. https://doi.org/10.3389/fpsyt.2018.00409

Beebe, B., Jaffe, J., Markese, S., Buck, K., Chen, H., Cohen, P., Bahrick, L., Andrews, H., & Feldstein, S. (2010). The origins of 12-month attachment: A microanalysis of 4-month mother–infant interaction. *Attachment Human Development, 12*(1-2), 3–141. https://doi.org/10.1080/14616730903338985

Benjamin, B. R., Valstad, M., Elvsåshagen, T., Jönsson, E. G., Moberget, T., Winterton, A., Haram, M., Høegh, M. C., Lagerberg, T. V., Steen, N. E., Larsen, L., Andreassen, O. A., Westlye, L. T., & Quintana, D. S. (2021). Heart rate variability is associated with disease severity in psychosis spectrum disorders. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 111*, Article 110108. https://doi.org/10.1016/j.pnpbp.2020.110108

Busuito, A., Quigley, K. M., Moore, G. A., Voegtline, K. M., & DiPietro, J. A. (2019). In Sync: Physiological correlates of behavioral synchrony in infants and mothers. *Developmental Psychology, 55*(5), 1034–1045. https://doi.org/10.1037/dev0000689

Capraz, Y. Z., Konrad, K., & Reindl, V. (2023). Concurrent and lagged physiological synchrony during mother-child interaction and their relationship to positive affect in 8- to 10-year-old children. *Scientific Reports, 13*(1), Article 17744. https://doi.org/10.1038/s41598-023-43847-8

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences (2nd ed.).*). Lawrence Erlbaum Associates.

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*, 674–691. https://doi.org/10.1002/dev.21743

Dean, R. T., & Dunsmuir, W. T. M. (2016). Dangers and uses of cross-correlation in analyzing time series in perception, performance, movement, and neuroscience: The importance of constructing transfer function autoregressive models. *Behavior Research Methods, 48*, 783–802. https://doi.org/10.3758/s13428-015-0611-2

Devita, S., Bozicevic, L., Deforges, C., Ciavarella, L., Tolsa, J.-F., Sandoz, V., & Horsch, A. (2024). Early mother-infant interactions within the context of childbirth-related posttraumatic stress symptoms. *Journal of Affective Disorders, 365*, 24–31. https://doi.org/10.1016/j.jad.2024.08.025

Devita, S., Deforges, C., Bickle-Graz, M., Tolsa, J.-F., Sandoz, V., & Horsch, A. (2023). Maternal childbirth-related posttraumatic stress symptoms, bonding, and infant development: a prospective study. *Journal of Reproductive and Infant Psychology*. https://doi.org/10.1080/02646838.2023.2261057

Feldman, R. (2007a). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry, 48*(3-4), 329–354. https://doi.org/10.1111/j.1469-7610.2006.01701.x

Feldman, R. (2007b). Parent–Infant Synchrony: Biological Foundations and Developmental Outcomes. *Current Directions in Psychological Science, 16*(6), 340–345. https://doi.org/10.1111/j.1467-8721.2007.00532.x

Feldman, R. (2012). Parent infant synchrony: A biobehavioral model of mutual influences in the formation of affiliative bonds. *Monographs of The Society for Research in Child Development*. https://doi.org/10.1111/j.1540-5834.2011.00660.x

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

Field, T., Healy, B., & LeBlanc, W. G. (1989). Sharing and synchrony of behavior states and heart rate in nondepressed mother-infant versus depressed interactions. *Infant Behavior and Development, 12*. https://doi.org/10.1016/0163-6383(89)90044-1

Firstbeat Technologies, O. *Retrieved from* ⟨https://www.firstbeat.com/en/⟩⟨⟩⟨https://www.firstbeat.com/en/⟩ (accessed on 30 November 2021).

Garthus-Niegel, S., Ayers, S., Martini, J., von Soest, T., & Eberhard-Gran, M. (2017). The impact of postpartum post-traumatic stress disorder symptoms on child development: a population-based, 2-year follow-up study. *Psychological Medicine, 47*(1), 161–170. https://doi.org/10.1017/S003329171600235X

Hamilton, J., & Alloy, L. (2016). Atypical reactivity of heart rate variability to stress and depression across development: Systematic review of the literature and directions for future research. *Clinical Psychology Review, 50*, 67–79. https://doi.org/10.1016/j.cpr.2016.09.003

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap)–a metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics, 42*(2), 377–381. https://doi.org/10.1016/j.jbi.2008.08.010

Hartmann, R., Schmidt, F. M., Sander, C., & Hegerl, U. (2019). Heart rate variability as indicator of clinical state in depression. *Frontiers in Psychiatry, 9*(735). https://doi.org/10.3389/fpsyt.2018.00735

Heyne, C.-S., Kazmierczak, M., Souday, R., Horesh, D., Berg, M. L.-v d, Weigl, T., Horsch, A., Oosterman, M., Dikmen-Yildiz, P., & Garthus-Niegel, S. (2022). Prevalence and risk factors of birth-related posttraumatic stress among parents: A comparative systematic review and meta-analysis. *Clinical Psychology Review*. https://doi.org/10.1016/j.cpr.2022.102157

Horesh, D., Garthus-Niegel, S., & Horsch, A. (2021). Childbirth-related PTSD: Is it a unique post-traumatic disorder? *Journal of Reproductive and Infant Psychology, 39*(3), 221–224. https://doi.org/10.1080/02646838.2021.1930739

Horsch, A., Garthus-Niegel, S., Ayers, S., Chandra, P., Hartmann, K., Vaisbuch, E., & Lalor, J. (2024). Childbirth-related posttraumatic stress disorder: definition, risk factors, pathophysiology, diagnosis, prevention, and treatment. *American Journal of Obstetrics and Gynecology*. https://doi.org/10.1016/j.ajog.2023.09.089

Ionio, C., & Di Blasio, P. (2014). Post-traumatic stress symptoms after childbirth and early mother-child interactions: An exploratory study. *Journal of Reproductive and Infant Psychology, 32*(2), 163–181. https://doi.org/10.1080/02646838.2013.841880

Jacob, S., Byrne, M., & Keenan, K. (2009). Neonatal physiological regulation is associated with perinatal factors: A study of neonates born to healthy african american women living in poverty. *Infant Mental Health Journal, 30*(1), 82–94. https://doi.org/10.1002/imhj.20204

Kärtner, J., & von Suchodoletz, A. (2021). The role of preacademic activities and adult-centeredness in mother-child play in educated urban middle-class families from three cultures. *Infant Behavior and Development, 64*, Article 101600. https://doi.org/10.1016/j.infbeh.2021.101600

Kranjec, J., Beguš, S., Geršak, G., & Drnovšek, J. (2014). Non-contact heart rate and heart rate variability measurements: A review. *Biomedical Signal Processing and Control, 13*, 102–112. https://doi.org/10.1016/j.bspc.2014.03.004

Leblanc, É ., Dégeilh, F., Daneault, V., Beauchamp, M. H., & Bernier, A. (2017). Attachment security in infancy: A preliminary study of prospective links to brain morphometry in late childhood. *Frontal Psychology, 8*, 2141. https://doi.org/10.3389/fpsyg.2017.02141

Leclere, C., Viaux, S., Avril, M., Achard, C., Chetouani, M., Missonnier, S., & Cohen, D. (2014). Why synchrony matters during mother child interactions: A systematic review. *Plos One, 9*(12). https://doi.org/10.1371/journal.pone.0113571

Lindsey, E. W. (2022). Shared positive emotion during parent-toddler play and parent and child well-being in Mexican origin families. *Infant Behavior and Development, 67*, Article 101706. https://doi.org/10.1016/j.infbeh.2022.101706

Messerli-Bürgy, N., Sandoz, V., Deforge, C., Lacroix, A., Sekarski, N., & Horsch, A. (2025). Stress responses of infants and mothers to a still-face paradigm after traumatic childbirth. *Psychoneuroendocrinology, 171*, Article 107222. https://doi.org/10.1016/j.psyneuen.2024.107222

Moore, G. A., & Calkins, S. D. (2004). Infants' vagal regulation in the still-face paradigm is related to dyadic coordination of mother–Infant interaction. *Developmental Psychology, 40*(6), 1068–1080.

Murray, L., & Karpf, J. (2000). *Coding Scheme For Structured Mother-infant Play Interaction at 12 months*. University of Reading.

Nguyen, T., Abney, D. H., Salamander, D., Bertenthal, B. I., & Hoehl, S. (2021). Proximity and touch are associated with neural but not physiological synchrony in naturalistic mother-infant interactions. *NeuroImage, 244*. https://doi.org/10.1016/j.neuroimage.2021.118599

Oliveira, V., von Rosenberg, W., Montaldo, P., Adjei, T., Mendoza, Shivamurthappa, Mandic, & Thayyil, S. (2019). Early postnatal heart rate variability in healthy newborn infants. *Frontiers in Physiology, 10*. https://doi.org/10.3389/fphys.2019.00922

Orth, U., Meier, L. L., Bühler, J. L., Dapp, L. C., Krauss, S., Messerli, D., & Robins, R. W. (2024). Effect size guidelines for cross-lagged effects. *Psychological Methods, 29*(2), 421–433. https://doi.org/10.1037/met0000499

Provenzi, L., Scotto di Minico, G., Giusti, L., Guida, E., & Müller, M. (2018). Disentangling the dyadic dance: Theoretical, methodological and outcomes systematic review of mother–infant dyadic processes. *Frontiers in Psychology, 9*, 348. https://doi.org/10.3389/fpsyg.2018.00348

R Core Team. (2023). R: A Language and Environment for Statistical Computing. ⟨https://www.R-project.org/⟩.

RStudio Team. (2020). RStudio: Integrated Development for R. RStudio. ⟨http://www.rstudio.com/⟩.

Sandoz, V., Deforges, C., Stuijfzand, S., Epiney, M., Vial, Y., Sekarski, N., & Horsch, A. (2019). Improving mental health and physiological stress responses in mothers following traumatic childbirth and in their infants: study protocol for the Swiss TrAumatic biRth Trial (START). *BMJ Open, 9*(12), Article e032469. https://doi.org/10.1136/bmjopen-2019-032469

Sandoz, V., Hingray, C., Stuijfzand, S., Lacroix, A., El Hage, W., & Horsch, A. (2022). Measurement and conceptualization of maternal PTSD following childbirth: Psychometric properties of the City Birth Trauma Scale—French Version (City BiTS-F). *Psychological Trauma: Theory, Research, Practice, and Policy, 14*(4), 696–704. https://doi.org/10.1037/tra0001068

Smith, C. G., Jones, E. J. H., Charman, T., & Wass, S. V. (2021). Anxious parents show higher physiological synchrony with their infants. *Psychological Medicine*, 1–11. https://doi.org/10.1017/S0033291720005085

Suga, A., Uraguchi, M., Tange, A., Ishikawa, H., & Ohira, H. (2019). Cardiac interaction between mother and infant: Enhancement of heart rate variability. *Scientific Reports, 9*(1), Article 20019. https://doi.org/10.1038/s41598-019-56204-5

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

Tan, G., Dao, T. K., Farmer, L., Sutherland, R. J., & Gevirtz, R. (2011). Heart rate variability (HRV) and posttraumatic stress disorder (PTSD): a pilot study. *Appl Psychophysiology Biofeedback, 36*(1), 27–35. https://doi.org/10.1007/s10484-010-9141-y

Weathers, F., Litz, B., Keane, T., Palmieri, P., Marx, B., & Schnurr, P. (2013). The PTSD Checklist for DSM-5 (PCL-5).

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