



## Mother and infant coordinate heart rhythms through episodes of interaction synchrony

Ruth Feldman<sup>a,b,\*,1</sup>, Romi Magori-Cohen<sup>c,1</sup>, Giora Galili<sup>b</sup>, Magi Singer<sup>b</sup>, Yoram Louzoun<sup>c</sup>

<sup>a</sup> Department of Psychology, Bar-Ilan University, Israel

<sup>b</sup> The Gonda Brain Sciences Center, Bar-Ilan University, Israel

<sup>c</sup> Department of Mathematics, Bar-Ilan University, Bar-Ilan University, Israel

### ARTICLE INFO

#### Article history:

Received 10 February 2011

Received in revised form 12 May 2011

Accepted 23 June 2011

#### Keywords:

Mother–infant interaction

Heart rhythm

Biological synchrony

Evolutionary models

Interaction synchrony

Mammalian parenting

### ABSTRACT

Animal studies demonstrated the powerful impact of maternal–infant social contact on the infant's physiological systems, yet the online effects of social interactions on the human infant's physiology remain poorly understood. Mothers and their 3-month old infants were observed during face-to-face interactions while cardiac output was collected from mother and child. Micro-analysis of the partners' behavior marked episodes of gaze, affect, and vocal synchrony. Time-series analysis showed that mother and infant coordinate heart rhythms within lags of less than 1 s. Bootstrapping analysis indicated that the concordance between maternal and infant biological rhythms increased significantly during episodes of affect and vocal synchrony compared to non-synchronous moments. Humans, like other mammals, can impact the physiological processes of the attachment partner through the coordination of visuo-affective social signals.

© 2011 Elsevier Inc. All rights reserved.

Parent–infant synchrony, a concept coined by the first researchers on parenting in social animals, describes the overarching process that coordinates the exchanges of hormonal, behavioral, and physiological stimuli between parent and infant during social contact, providing critical inputs for growth and development of the young (Rosenblatt, 1965; Schneirla, 1946; Wheeler, 1928). Through early social contact, mammalian mothers adapt their physiological systems those of the infant's and this experience organizes infant growth (Schanberg, Ingledue, Lee, Hannun, & Bartolome, 2003), shapes brain structures that modulate the stress response (Champagne, 2008), sets the biological clock (Hofer & Shair, 1982), and regulates heart rhythms (Hofer, 1971). Synchrony is a time-bound experience marked by an early sensitive period. Maternal separation or variations in maternal care during the post-birth period permanently alter systems that modulate stress or enable social adaptation (Meaney, 2010), highlighting the need to understand the effects of social contact on the human infant's physiology. Of special interest is whether mother–infant interactions shape the infant's physiology in a moment-to-moment fashion, a question that may be addressed by assessing the online coordination of maternal and infant's heart rhythms during social contact.

Studies in mammals addressed two mechanisms by which mothers organize the infant's physiology by means of social contact. The first considers the mother's physical presence and full bodily contact. Hofer (1995) demonstrated that the maternal physical presence integrates a set of bio-behavioral provisions, such as maternal heart rhythms, body heat, odor, or nursing, and each functions to regulate a specific system in the pup. The second mechanism involves the species-specific set of maternal postpartum behaviors. For instance, maternal licking-and-grooming, a typical behavior of rat mothers in the immediate post-birth period, was found to exert a lifelong impact on the infant's stress response and the capacity to

\* Corresponding author at: Department of Psychology and the Gonda Brain Sciences Center, Bar-Ilan University, Ramat-Gan 52900, Israel. Tel.: +972 3 531 7943; fax: +972 3 535 0267.

E-mail address: feldman@mail.biu.ac.il (R. Feldman).

<sup>1</sup> These authors contributed equally to this work.

provide optimal parenting to the next generation (Champagne, 2008). Both mechanisms impact the organization of heart rhythms in young mammals (Dettling, Schnell, Maier, Feldon, & Price, 2007; Hofer, 1971), pointing to the openness of the autonomic system to maternal social influences. Yet, despite the importance of bio-behavioral synchrony to the infant's lifetime adaptation, the online coordination of physiological and behavioral stimuli between human mothers and their infants during social contact received little attention. It is thus unclear whether bio-behavioral synchrony occurs in humans, whether human synchrony requires physical contact as it does in other mammals, and whether social interactions contribute to the online regulation of the infant's heart rhythms.

Social interactions between human mothers and infants draw on their mammalian heritage yet are unique in several aspects. Interactions between human mothers and infants often serve a purely social function that is not directed toward feeding, care, or protection. Humans are also the only species where early social play revolves around the matching of socio-affective facial signals. During the third month of life, infants begin to partake in face-to-face interactions that are marked by synchrony of non-verbal cues, including mutual gazing, co-vocalizations, and the matching of affective expression (Stern, 1985; Tronick, 1989). Interaction synchrony plays an important role in the maturation of brain circuits that support social engagement and the experience of synchrony within the sensitive period of 3–6 months contributes to cognitive, social, and emotional growth (Feldman, 2007a; Johnson et al., 2005; Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001). Moreover, interaction synchrony at 3 months provides the foundation for purely human achievements and predicts the development of complex symbolic expression and the capacity for dialogical empathy across childhood and up to adolescence (Feldman, 2007b,c).

Face-to-face interactions are organized in a clear rhythmic structure. Episodes of social engagement are followed by episodes of rest and sequences of specific behaviors are repeated throughout the interactive event (Cohn & Tronick, 1987; Kaye & Fogel, 1980). Three main channels of nonverbal synchrony have been identified. Gaze synchrony (G), the matching of social gaze between parent and child, sets the framework for social relatedness and contributes to cognitive growth (Kaye & Fogel, 1980). Affect synchrony (A), the matching of affective expression, plays an important role in the development of self-regulatory capacities (Cohn & Tronick, 1988). Finally, parents and infants often engage in “proto-conversations” and these repetitive moments of vocal synchrony (V) serve as the building blocks of spoken language and promote attachment security (Jaffe et al., 2001). Each of these forms of synchrony has shown to predict long-term outcome and is thought to provide essential environmental inputs for physiological and social growth. One potential mechanism by which gaze, affect, and vocal synchrony shape development may be that these moments facilitate, singly or in combination, biological synchrony between the mother and infant's heart rhythms. Such biological synchrony may support the infant's autonomic maturation by means of social contact.

Research has pointed to the links between interaction synchrony and maternal and infant's cardiac vagal tone – the respiratory component in heart rate variability (RSA). Following synchronous play infants showed a greater vagal-tone suppression to the still-face, indicating that synchrony facilitates a more adaptive autonomic response to stress (Moore & Calkins, 2004), and similar findings were reported for mothers (Moore et al., 2009). Similarly, correlations were found between infant recovery from the still-face and maternal and infant RSA (Ham & Tronick, 2006) and between mother's and infant's RSA and interaction synchrony (Feldman, Singer, & Zagoory, 2010). Overall, it has been suggested that such fit between maternal and infant physiology during social contact supports the development of infant physiological regulation through the entrainment of biological rhythms (Feldman, 2006) and contributes to the consolidation of a unique bio-behavioral attachment between mother and child, which provides the foundation for the infant's physiological, social, and emotional growth (Carter et al., 2005). However, these studies describe the overall associations between maternal and infant's autonomic response and relational behavior but do not address the second-by-second coordination of physiology and behavior between attachment partners during social contact.

In light of the above, the present study had two goals. First, we examined whether face-to-face interactions would lead to biological synchrony between the mother's and the infant's heart rhythms. Second, we examined whether the three forms of synchrony – gaze, affect, and vocal synchrony – function to increase the degree of biological synchrony between maternal and infant's heart rhythms. We thus compared the degree of biological synchrony during synchronous episodes to that observed during non-synchronous moments for each form of synchrony and for the rare moments in which all three forms of synchrony occurred simultaneously. Our hypothesis was that mother–infant interaction synchrony provides one mechanism by which the social context regulates the human infant's physiology in an ongoing, moment-by-moment manner.

## 1. Method

### 1.1. Participants

Forty 3-month old healthy infants (15 females,  $M = 13.92$  weeks,  $SD = 1.15$ ) and their mothers participated. Mothers were recruited in two tertiary care hospitals on the 2nd post-birth day and were screened for anxiety and depression in the postpartum and again at 3 months. Mothers were healthy, delivered a singleton term healthy baby, were above 21 years, had at least high-school education, were married or cohabitating, and were of Israeli-Jewish ethnicity. Mothers' age averaged 28.9 years ( $SD = 4.0$ ) and they completed 14.6 ( $SD = 2.3$ ) years of education.

## 1.2. Procedure and measures

Mothers and infants visited a university laboratory during the morning hours when the infant was fed and rested. Upon arrival, mothers signed an informed consent. Infant sat in an infant-seat mounted on a table and mother sat facing him/her. Both mother and infant were connected to ECG monitor-IBI logger. Approximately two minutes were allowed to get accustomed to the electrodes. Following, mothers were instructed to play freely with the infant for 3 min and face-to-face interactions were videotaped using two cameras placed on adjacent walls and a split-screen video mixer controlled from an adjoined room.

ECG signals of mother and infant were simultaneously sampled during the interaction by a dual channel portable ECG monitor-IBI logger system (12bit, 1000 samples/second/channel, 3992/6 – IBI BioLog<sup>®</sup> System, UFI, Morro Bay, CA). The 'BioLog' system was equipped with active signal-conditioning electrodes, attached to participants using three disposable Ag–AgCl skin surface electrode patches.

Inter-Beat-Intervals (IBI) series were produced from ECG signals. IBI series were visually scanned for segments with multiple outliers. The IBI series were linearly interpolated to form an evenly sampled time-series and a high-pass filter of  $h > 0.05$  Hz was used. Consistent with Khattak et al. (2007), the high-pass filter was performed through a subtraction of a 20-s running average from each data point. The first and last 10 s of the data were omitted to avoid artifacts due to the removal of the average. Filtering at the electrode level allows for better signal-to-noise ratio and minimizes artifacts due to movements. QRS complexes of the ECG signal were detected online using band check thresholding followed by "Descending Train" peak detection algorithm. Discrete Inter-Beat-Intervals series ( $IBI, R_i - R_{i-1}$  in ms) were stored for off line processing. Each IBI series was visually scanned by two researchers for outlier caused by artifacts or ectopic beats.

Maternal and infant's behaviors were micro-coded on a computerized system (Noldus, The Wagginiggen, NL) for 3 categories of behavior: Gaze, Affect, and Vocalization. Each category included a set of mutually exclusive behaviors as follows.

*Parent codes: Parent gaze*—this category assessed the direction of parent gaze and included the following codes: gaze to infant's face, gaze to object or environment, and gaze aversion – indicating that parent gazes away from the infant but gaze is not focused on other objects or the environment. *Parent affect*—parent's expressed affect was coded on the basis of facial expressions, body tone, movements, and other non-verbal signals and included positive, neutral, and negative affective expression. *Parent vocalizations*—the parent's vocal output was coded along four codes: "motherese" vocalizations – infant-directed speech that is high-pitched and typically includes sing-song vocalizations; "typical" adult speech to the infant in a normal range and regular rhythm; adult speech to other adult; and no speech.

*Infant codes: Infant gaze*—was coded similar to parent's gaze along the following codes: gaze to parent, gaze to object or environment, and gaze aversion. *Infant affect*—was similarly coded as positive, neutral, or negative. *Infant vocalizations*—included positive vocalizations, such as positive babbling, cooing, or giggles, negative vocalizations, including fussing and crying, and no vocalizations. Inter-rater reliability, computed for 10 interactions (25%), averaged 94%,  $kappa = .86$  (range = .80–.98). Consistent with previous research (Feldman, 2007a), three forms of synchrony were computed using conditional probabilities: *Gaze synchrony*—the proportion of time mother and infant were in social gaze and looked at each other. *Affect synchrony*—the proportion of time mother and infant matched their positive affect, and *Vocal synchrony*—proportion of time mother and child emitted positive vocalizations simultaneously.

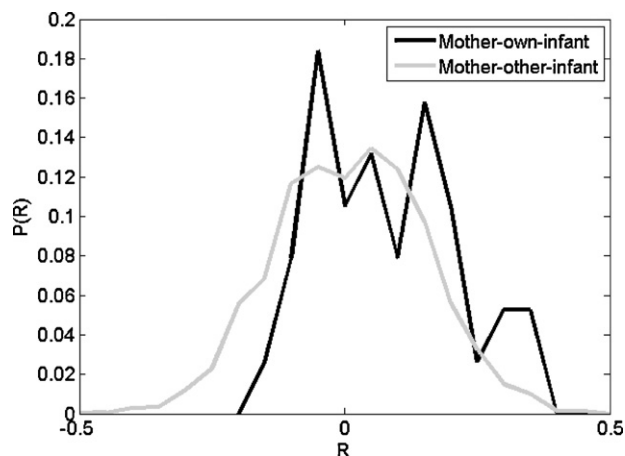
## 2. Results

### 2.1. First study question: time-series analysis of maternal and infant heart rhythms

*Time-series analysis:* following research on mother–infant interaction synchrony, synchrony between maternal and infant heart rhythms was computed for each dyad using a time-domain time-series analysis (Cohn & Tronick, 1988; Gottman, 1981). These time-series analysis computed the Cross Correlation Functions (CCFs) between the IBI series of each mother and infant following ARIMA modeling. For each mother–infant CCF, the following statistical tests were used:

- (A) A two-sided *t*-test of the *R* values of all mother–infant pairs versus a null hypothesis of an average 0 correlation. Note that this is a conservative estimate, since we were interested to assess whether the correlation is positive and indicates relations between maternal and infant heart rhythms.
- (B) A *t* test of the *R* values of all mother–infant pairs versus a null hypothesis of an average 0 correlation, following an ARIMA analysis of the mother–infant pairs. The ARIMA was performed using one autoregressive term and one moving average term. No time-lag was used.

In order to demonstrate that the synchrony between mother and infant's heart rhythms is significantly greater than chance, we created a distribution from the cross-correlation coefficients that resulted from the CCF analysis of each mother–infant pair and compared it to a distribution of coefficients that resulted from a similar CCF analysis of mothers and random infants (i.e., other infants in the sample) in order to assess whether the distribution of mother–infant cross-correlation coefficients was significantly greater than chance. The two distributions are presented in Fig. 1. The distribution of cross-correlation coefficients from the mothers–infants CCF analysis (Fig. 1, dark line) was positive and significantly



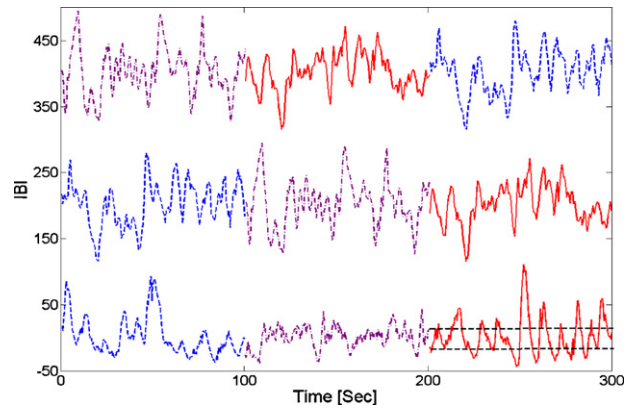
**Fig. 1.** Histogram of mother–infant cross-correlation coefficients as compared to random mother–infant dyads. Coefficients of the cross-correlation function (CCF) derived from the time-series analysis of each mother–infant dyad after the autocorrelated component in each time-series was removed using ARIMA modeling. The distribution of these coefficients (dark line) is skewed toward positive values. A similar distribution created from the cross-correlation coefficients derived from the time-series analysis of random mother–infant dyads (gray line) is centered around zero, as expected. The two distributions are significantly different ( $t < .01$ , one tail).

greater than chance ( $t = 4.92$ ,  $p < .002$ ). Furthermore, when comparing the two distributions a significant difference was found ( $t = 3.84$ ,  $p < .01$ ).

Similar results were obtained after removing the autocorrelated component in each time series, using Autoregressive Integrated Moving Average (ARIMA) models for each time-series (Gottman, 1981), with one autoregressive term and one moving average term. Prior to computing these separate ARIMA models, the series were inspected for stationarity conditions (i.e., consistency of mean and variance across the time-series). Following, the CCFs for each dyad were computed using the two series of residuals from the ARIMA modeling with no time-lag in the analysis. These correlations coefficients indexed the degree of synchrony between the two time-series above and beyond the internal rhythms in each partner's heart rhythms. The correlation coefficients were again positive on average and significantly different than 0 ( $t$  test score = 2.04,  $p < .05$ ). These findings demonstrate that the synchrony between mother and infant's heart-rhythm is non-random, confirming our first hypothesis.

**Bootstrapping analysis:** to address the second study question, a bootstrapping method was used. For this end, the first 100 s of each mother's IBIs were combined to produce a long time-series of 4000 s ( $100 \times 40$ ). This process was repeated with the related infant's IBI (each time-series contained over 10,000 IBI data points). The Pearson cross-correlation coefficient of the mother and her own infant's combined time-series was .06 with an extremely high  $p$  value of less than  $1e^{-10}$ . However, in order to achieve a more precise estimate of the significance of the results while controlling for the autocorrelated component in each time-series, the bootstrapping approach was used. We compared the Pearson cross-correlation coefficient of the combined time-series of the 40 mothers and related-infant pairs to the Pearson correlation coefficient obtained from randomizing the order of the infant's IBI time-series. Each randomized sequence was composed of 40 sections of 100 s of infant IBI. In the randomized sequences, each 100 s of mother IBI were compared to a similar chunk of a infant IBI, but not her own infant (Fig. 2). The bootstrapping analysis provides a comparison between the cross-correlations of the related-mother–infant-pairs and the cross-correlations of the  $40 \times 39$  possible unrelated-mother–infant pairs. One thousand randomized comparisons were performed and the Pearson cross-correlation coefficient was computed for each. The significance of the bootstrapping algorithm is defined as the fraction of randomized time-series with a cross-correlation higher than the 40 mother-own infant IBI time-series. The cross-correlation of the *mother-own-infant pairs* for each pair was significantly higher than the cross-correlation between the *mother-other-infant-pairs* in the vast majority of randomizations ( $p = .02$ ) (Fig. 3). These findings further demonstrate the phenomenon of heart-rhythm synchrony between mother and infant during social interaction is observed.

To further understand the bootstrapping results, we examined whether the observed cross-correlations indeed stem from IBI synchrony or from data artifacts. We tested whether IBI acceleration/deceleration of the mother leads to IBI acceleration/deceleration of her infant and vice versa. To examine this, we detected events of significant rise in the infant's IBI and checked whether the mother showed a parallel increase. To detect events of increased infant IBI, we computed all peaks in the infant IBI time-series and defined these peaks as outliers. IBI outliers as defined as all events of infant IBI higher than 2 standard deviations (SDs) of the infant's IBI average. The decision to use 2 SDs resulted from visual inspection of the IBI time-series and intended to include the majority of peaks in the infant's IBI (see Fig. 2 for example). For each such outlier event (single time point), we measured the IBI pattern of both mother and infant starting 2 s before the outlier event and ending 10 s after the outlier event. The 10-s interval was chosen to enable a long enough period to include both a long rise and a decrease of IBI. These time-segments of high outlier events were then averaged to produce an averaged time-series.

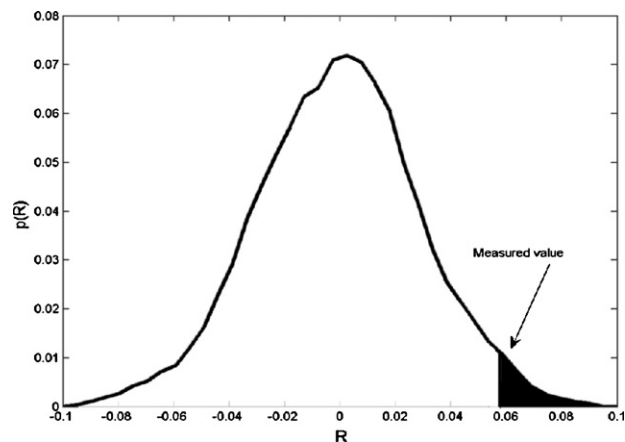


**Fig. 2.** An example of the bootstrapping methodology. The bottom row represents the combined infants' IBI time-series (first 100 s of each infant's IBI) for three random infants used for demonstration (the actual analysis used all 40 mothers and infants in the same manner). The middle row represents the combined IBI time-series of their three mothers. The top row is similar to the middle row but the positions of the three mothers and three infants are randomized. The cross-correlation between the lower and middle row represents the actual synchrony between the mothers' and their own infants' IBI, whereas the correlations between the lower and upper row are used for the bootstrapping analysis. The dashed horizontal lines at the lower left corner represent the cutoff used to detect outliers.

By definition, the averaged infant IBI segments initialized on the infant's IBI high outlier event series shows a peak slightly after time zero. However, if the mother and her own infant's IBI are synchronized, the same pattern would be expected to appear in the averaged mother IBI segment initialized on own infant's high outlier events. Averaging over a large number of mother IBI random segments would produce a flat curve, whereas the only mechanism that can explain the rise observed in Fig. 3 in the averaged IBI mother segments is that the segments are not random and that the two sets of outlier segments are synchronized. The same procedure was repeated using the mother's high IBI outlier events with similar results. Fig. 4 represents the averaged mother and infant's IBI segments, initiated on the infant/mother high outlier events. As seen, mother's and infant's IBIs peak nearly simultaneously. These findings demonstrate that the correlation observed in Fig. 3 is the direct result of IBI synchrony, with a near-zero time-lag.

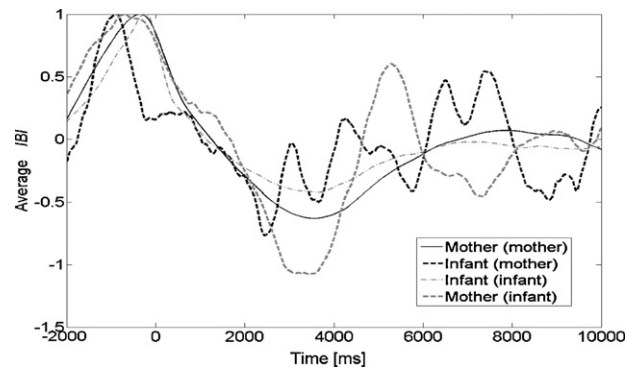
A similar analysis was performed for the low IBI outlier events, defined as IBI values lower than one-and-a-half SDs below the average heart rate. We similarly chose 1.5 SDs based on the visual inspection of the time-series. Similar to the high outlier segments, a decrease in the infant's/mother's IBI resulted in a decrease in the mother's/infant's IBI at a near-zero time-lag (Fig. 3). Note that the high and low outliers were defined differently, since the infant's IBI curve is not symmetric (Fig. 2), and the low part of the IBI curve is slightly flatter than the high part of the same curve and thus, a lower threshold was used.

Results of both the time-domain time-series analysis and the bootstrapping analysis clearly demonstrate that the mother's and her own infant's IBI are partially correlated. This heart rhythm correlation is the direct result of a near-zero-time-lag heart-rhythm synchronization, in which an increase in the infant's heart rhythm leads to an increase in the mother's heart rhythm, and a decrease in the infant's heart rhythm leads to a decrease in the mother's heart rhythm and vice versa.



**Fig. 3.** Results of the bootstrapping analysis comparing related-mother-infant-pairs IBI synchronization and unrelated-mother-infant-pairs IBI synchronization. The black region represents the fraction of  $R$  values obtained from the bootstrapping analysis (unrelated-mother-infant-pairs) that is higher than the observed cross-correlation of the related-mother-infant-pairs analysis.





**Fig. 4.** Results of the bootstrapping analysis showing synchrony in the acceleration and deceleration of mother and her infant's IBI. Events of high infant IBI ( $>2$  SDs of average IBI) were initialized on the mother's high IBI events and vice versa. Parallel analysis was performed for the infant's low IBI ( $<1.5$  SDs of average IBI) synchronized on the mother's low IBI events and vice versa. A peak in the mother's IBI was accompanied by a peak in her infant's IBI and vice versa.

## 2.2. Second study question: concordance in heart rhythms increases during episodes of interaction synchrony

The IBI synchronization of mother and her own infant was not consistent across the interaction: periods of high IBI synchronization were surrounded by periods of non-synchronized IBIs. To address the second study question, we measured the IBI synchronization during periods of interaction synchrony and checked the level of synchrony within these periods as compared to the rest of the interaction. The proportions of time dyads spent in each form of synchrony appear in Table 1. The cross-correlation coefficients during the synchronized episodes were again computed by combining all episodes of a specific form of synchrony (G, A, V, and their combinations) into a single sequence and computing the cross-correlation between the mother's and her own infant's IBIs during these episodes as compared to the rest of the interaction.

All mother-own infant synchronized episodes had positive correlations at extremely low  $p$  values ( $p < 1e^{-10}$ ). However, to further specify the meaning of these results, a similar bootstrapping method was used. The synchronous episodes were compared to similar episodes from the randomized time-series. For instance, if a certain form of synchrony lasted 20, 35, and 15 s scattered over the entire interaction, similar periods with a similar scatter were used from the randomized sequence to perform the bootstrapping analysis. The cross-correlation coefficients from the bootstrapping analysis and their significance levels are presented in Table 1. These results indicate that two forms of synchrony were most effective in increasing IBI synchrony: vocal synchrony (V) and affect synchrony (A). During periods of vocal or affect synchrony IBI synchrony increased significantly as compared to the rest of the interaction. As seen, IBI synchrony further increased when affect and vocal synchrony co-occurred (note that we did not check  $p$  values below 0.001, since only 1000 bootstrapping comparisons were performed). In contrast, gaze synchrony (G) in of itself did not increase IBI synchrony. These results support our second hypothesis and show that during moments of vocal and affect synchrony, the synchrony between the mother's and her infant's heart rhythms increases significantly.

## 3. Discussion

Results of the present study demonstrate that human mothers and infants engage in a process of bio-behavioral synchrony as it was initially defined in other mammals – the regulation of infant physiology by means of social contact. During face-to-face interactions mothers adapt their heart rhythms to those of their infant's and infants, in turn, adapt their rhythms to those of the mother's within lags of less than 1 s, forming biological synchrony in the acceleration and deceleration of heart rate. Not only were biological rhythms coordinated, they were matched online with the degree of interactive synchrony in

**Table 1**

Proportions of time dyads engaged in each form of synchrony and the cross-correlation coefficient between related-mother–infant-pairs IBIs during synchronous compared to non-synchronous episodes.

	M	SD	R	$p$
Gaze synchrony (G)	.85	.33	.029	.109
Affect synchrony (A)	.42	.35	.090	.004
Vocal synchrony (V)	.13	.11	.096	.001
Gaze and affect synchrony (GA)	.36	.32	.036	.086
Gaze and vocal synchrony (GV)	.10	.13	.083	.041
Affect and vocal synchrony (AV)	.07	.12	.142	<.000
Affect, vocal and gaze synchrony (AVG)	.06	.11	.09	.069

Note:  $p$  represent the cross-correlation probability of accepting the NULL hypothesis (no correlation) obtained from bootstrapping analysis.

the vocal and affective modalities. During episodes of synchrony between the partners' social cues, the degree of biological concordance between their heart rhythms increased accordingly. These findings suggest the online coordination between the physiological and social processes of separate individuals within an attachment relationship.

Although the findings point to continuity between humans and other mammals, important species differences are also noted. In order for the physiological processes of one human being to impact those of the attachment partner's, neither of the aforementioned mammalian mechanisms of synchrony were required – physical proximity that involves full bodily contact (Hofer, 1995) or maternal behavior consisting mainly of tactile stimulation (Meaney, 2010). Mothers and infants were not situated in a position of physical contact and touched each other rarely and thus, another mechanism was at work here that did not build on physical touch and was sensitive to finely tuned moment-by-moment alterations in communicative intent. Possibly, the human capacity to impact the physiological processes of the attachment partner's through the coordination of facial and vocal signals represents abilities that distinguish humans from other mammals, lie at the core of human attachment, and provide the collaborative basis for the formation of human societies (Moll & Tomasello, 2007). Infants are initiated into this bio-behavioral exchange as soon as they enter the social world and begin to engage in face-to-face interactions. Such experiences may provide critical inputs for the child's ultimate physical growth, social adaptation, and – similar to other mammals – the ability to form optimal attachment in the next generation.

What may be the mechanisms through which biological synchrony promotes infant development? One possibility is that, similar to the findings for other mammals (Hofer, 1995), such physiological synchrony functions to entrain the infant's biological rhythms, thereby providing an external regulation to the consolidation of cyclic physiological processes occurring in milliseconds (e.g., heart rhythms), days (e.g., circadian rhythms), or seasons (e.g., seasonal hormonal release). More optimal organization of such biological rhythms in the first months of life has shown to predict the development of self-regulatory and interactive capacities across the first years of life (Feldman, 2006, 2009). The second mechanism may relate to the formation of a specific bio-behavioral attachment bond between mother and infant, which is supported by a unique fit between the partners' physiology and behavior (Barrett & Fleming, 2011). Such dyad-specific attachment that coordinates biological and social processes forms what Bowlby (1969) has termed as an "Internal Working Model" and provides the basis for the infant's physical and social growth and the capacity to engage in future attachment relationships.

The repetitive-rhythmic experience of human synchrony has been likened to the learning of a birdsong in terms of its implications for infant growth and social adaptation (Williams, 2004). The learning of a birdsong involves a finely tuned interplay between specific brain structures, neuro-chemical systems, epigenetic influences, imitative learning, and error detection, all within a very narrow time-window, else the structural changes that enable song production are disrupted and the bird's fittedness into the pack may be impaired (Jarvis, 2004). Songbirds learn with remarkable precision the tonal, rhythmic, and structural characteristics of their species' song, similar to the human infant's impressive capacity to perceive the rhythmic and affective features of its mother's interactive style (Margliash, 2002). While the songbird's model provide useful insights for the human infant's ultimate adaptation, the findings also underscore the uniqueness of the face-to-face exchange and the flexibility it offers for the infant's social engagement. Unlike birds, human infants can impact in real time both the behavioral parameters of the social process and their biological underpinnings. Such mutually adaptive bio-behavioral process affords infants a relational experience that does not follow a predetermined pattern of the species but is co-created in the present moment from the contributions of mother and child.

Face-to-face exchanges are short events spread across the daily routine of parent and child that mark purely social moments and involve higher levels of positive arousal and social coordination as compared to episodes of caregiving or feeding. The brevity and intensity of such moments appear to initiate a process of biological concordance between the partners' heart rhythms. As seen, during episodes of high positive arousal – for instance, moments of vocal or affective synchrony which are accompanied by high positive energy – the tightness of this biological synchrony increased. The data indeed show that gaze synchrony in of itself, defining moments of social attunement without a rise in positive arousal, did not increase biological synchrony. Possibly, the early experience of such intense moments within attachment relationships sets the possibility that close relationships, throughout the lifespan, may integrate the individual's affective state and physiological systems into an interpersonal event that affords the online coordination of physiological and social processes between two individuals within an attachment bond.

The data analytic approach employed here combined two methods for analyzing the temporal coordination between two series of events to demonstrate the phenomenon of heart-rhythm concordance. Time-domain time-series analysis has been the typical approach in research on interaction synchrony (Cohn & Tronick, 1988; Feldman, 2007a, 2007b, 2007c; Feldman, Greenbaum, & Yirmiya, 1999; Field, Healy, Goldstein, & Guthertz, 1990; Gottman, 1981; Jaffe et al., 2001). Bootstrapping analysis has similarly been used to study the coordination of non-verbal patterns during social interaction in infants (Yale, Messinger, Cobo-Lewis, & Delgado, 2003), the coordination of emotional behavior between adults during psychotherapy (Pascual-Leone, 2009), and the associations between the behaviors of social partners in adolescence (Zimmer-Gembeck, Chipuer, Hanisch, Creed, & McGregor, 2006). Bootstrapping methods have been particularly useful in analyzing heart-rate data and are especially suited for handling cardiac output that includes high level of noise (Couderc, Xiaojuan, Zareba, & Moss, 2005; Wasserman & Bockenholt, 1989). The present study is the first, to our knowledge, to combine the two approaches in a single study.

Future research is required to examine the impact of interaction synchrony on other physiological processes, such as hormonal release or brain activation, and assess high-risk conditions, for instance, postpartum depres-

sion or premature birth, that may interfere with the formation of bio-behavioral synchrony. Research in humans should follow animal models in detecting specific genetic markers, epigenetic effects, and brain systems implicated in the online coordination of biological and relational processes by means of social contact beginning with the infant's first interactions with the mother and continuing with the individual's attachment relationships throughout life.

## Acknowledgements

Research in Dr. Feldman's lab during the study period was supported by the Israel Science Foundation (#1318/08), the NARSAD Foundation (independent investigator award), the Katz family foundation, and the Irving B. Harris Foundation.

## References

- Barrett, J., & Fleming, A. S. (2011). All mothers are not created equal: Neural and psychobiological perspectives on mothering and the importance of individual differences. *Journal of Child Psychology and Psychiatry*, 52, 368–397.
- Bowlby, J. (1969). *Attachment and loss. Vol. 1: Attachment*. New York: Basic.
- Carter, C. S., Ahnert, L., Grossmann, K. E., Hrdy, S. B., Lamb, M. E., Porges, S. W., & Sachser, N. (Eds.). (2005). *Attachment and bonding: A new synthesis*. Boston, MA: The MIT Press.
- Champagne, F. A. (2008). Epigenetic mechanisms and the transgenerational effects of maternal care. *Frontiers in Neuroendocrinology*, 29, 386–397.
- Cohn, J. F., & Tronick, E. Z. (1987). Mother–infant face-to-face interaction: The sequencing of dyadic states at 3, 6, and 9 months. *Developmental Psychology*, 23, 68–77.
- Cohn, J. F., & Tronick, E. Z. (1988). Mother–infant interaction: Influence is bidirectional and unrelated to periodic cycles in either partner's behavior. *Developmental Psychology*, 24, 386–392.
- Couderc, J. P., Xiaojuan, X., Zareba, W., & Moss, A. J. (2005). Assessment of the stability of the individual-based correction of QT interval for heart rate. *Annals of Noninvasive Electrocardiology*, 10, 25–34.
- Detting, A. C., Schnell, C. R., Maier, C., Feldon, J., & Pryce, C. R. (2007). Behavioral and physiological effects of an infant–neglect manipulation in a bi-parental, twinning primate: Impact is dependent on familial factors. *Psychoneuroendocrinology*, 32, 331–349.
- Feldman, R., Greenbaum, C. W., & Yirmiya, N. (1999). Mother–infant affect synchrony as an antecedent to the emergence of self-control. *Developmental Psychology*, 35, 223–231.
- Feldman, R. (2006). From biological rhythms to social rhythms: Physiological precursors of mother–infant synchrony. *Developmental Psychology*, 42, 175–188.
- 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, 329–354.
- Feldman, R. (2007b). On the origins of background emotions: From affect synchrony to symbolic expression. *Emotion*, 7, 601–611.
- Feldman, R. (2007c). Mother–infant synchrony and the development of moral orientation in childhood and adolescence: Direct and indirect mechanisms of developmental continuity. *American Journal of Orthopsychiatry*, 77, 582–597.
- Feldman, R. (2009). The development of regulatory functions from birth to five years; Insights from premature infants. *Child Development*, 80, 544–561.
- Feldman, R., Singer, M., & Zagoory, O. (2010). Touch attenuates infants' physiological reactivity to stress. *Developmental Science*, 13, 271–278.
- Field, T., Healy, B., Goldstein, S., & Guthertz, M. (1990). Behavior-state matching and synchrony in mother–infant interaction of nondepressed versus depressed dyads. *Developmental Psychology*, 26, 7–14.
- Gottman, J. M. (1981). *Time-series analysis: A comprehensive introduction for social scientists*. Cambridge University Press.
- Ham, J., & Tronick, E. (2006). Infant resilience to the stress of the still-face: Infant and maternal psychophysiology are related. *Annals of the New York Academy of Sciences*, 1094, 297–302.
- Hofer, M. A. (1971). Cardiac rate regulated by nutritional factor in young rats. *Science*, 172, 1039–1041.
- Hofer, M. A. (1995). Hidden regulators: Implications for a new understanding of attachment, separation, and loss. In S. Golberg, R. Muir, & J. Kerr (Eds.), *Attachment theory: Social, developmental, and clinical perspectives* (pp. 203–230). Hillsdale, NJ: Analytic Press.
- Hofer, M. A., & Shair, H. (1982). Control of sleep-wake states in the infant rat by features of the mother–infant relationship. *Developmental Psychobiology*, 15, 229–243.
- Jaffe, F., Beebe, B., Feldstein, S., Crown, C. L., & Jasnow, M. D. (2001). Rhythms of dialogue in infancy. *Monographs of the Society for Research in Child Development*, 66 (2, Serial No. 265).
- Jarvis, E. D. (2004). Learned birdsong and the neurobiology of human language. *Annals of the New York Academy of Sciences*, 1016, 746–777.
- Johnson, M. H., Griffin, R., Csibra, G., Halit, H., Farroni, T., de Haan, M., et al. (2005). The emergence of the social brain network: Evidence from typical and atypical development. *Development and Psychopathology*, 17, 599–619.
- Khattak, A. Z., Padhye, N. S., Williams, A. L., Lasky, R. E., Moya, F. R., & Verklan, M. T. (2007). Longitudinal assessment of heart rate variability in very low birth weight infants during their NICU stay. *Early Human Development*, 83, 361–366.
- Kaye, K., & Fogel, A. (1980). The temporal structure of face-to-face communication between mothers and infants. *Developmental Psychology*, 16, 454–464.
- Margliash, D. (2002). Evaluating theories of bird song learning: Implications for future directions. *Journal of Comparative Physiology. A, Neuroethology, Sensory, Neural, and Behavioral Physiology*, 188, 851–866.
- Meaney, M. J. (2010). Epigenetics and the biological definition of gene × environment interactions. *Child Development*, 81, 41–79.
- Moll, H., & Tomasello, M. (2007). Cooperation and human cognition: The Vygotskian intelligence hypothesis. *Philosophical Transactions of the Royal Society of London*, 362, 639–648.
- Moore, G., & Calkins, S. D. (2004). Infants' vagal regulation in the still-face paradigm is related to dyadic coordination of mother–infant interaction. *Developmental Psychology*, 40, 1068–1080.
- Moore, G. A., Hill-Soderlund, A. L., Propper, C. B., Calkins, S. D., Mills-Koonce, W. R., & Cox, M. J. (2009). Mother–infant vagal regulation in the face-to-face still-face paradigm is moderated by maternal sensitivity. *Child Development*, 80, 209–223.
- Pascual-Leone, A. (2009). Dynamic emotional processing in experiential therapy: Two steps forward, one step back. *Journal of Consulting & Clinical Psychology*, 77, 113–126.
- Rosenblatt, J. S. (1965). The basis of synchrony in the behavioral interaction between the mother and her offspring in the laboratory rat. In B. M. Foss (Ed.), *Determinants of infant behavior* (pp. 3–45). London: Methuen.
- Schanberg, S. M., Ingledue, V. F., Lee, J. Y., Hannun, Y. A., & Bartolome, J. V. (2003). PKC alpha mediates maternal touch regulation of growth-related gene expression in infant rats. *Neuropsychopharmacology*, 28, 1026–1030.
- Schneirla, T. C. (1946). Problems in the biopsychology of social organizations. *Journal of Abnormal and Social Psychology*, 41, 385–402.
- Stern, D. N. (1985). *The interpersonal world of the infant: A view from psycho-analysis and developmental psychology*. New York: Basic Books.
- Tronick, E. Z. (1989). Emotions and emotional communication in infants. *American Psychologist*, 44, 112–126.
- Wasserman, S., & Bockenholt, U. (1989). Bootstrapping: Applications to psychophysiology. *Psychophysiology*, 26, 208–221.
- Wheeler, W. M. (1928). *The social insects*. New York: Harcourt.



- Williams, H. (2004). Birdsong and singing behavior. *Annals of the New York Academy of Sciences*, 1016, 1–30.
- Yale, M. E., Messinger, D. S., Cobo-Lewis, A. B., & Delgado CF. (2003). The temporal coordination of early infant communication. *Developmental Psychology*, 39, 815–824.
- Zimmer-Gembeck, M. J., Chipuer, H. M., Hanisch, M., Creed, P. A., & McGregor, L. (2006). Relationships at school and stage-environment fit as resources for adolescent engagement and achievement. *Journal of Adolescence*, 29, 911–933.