ORIGINAL ARTICLE

WILEY

Interpersonal synchrony is associated with infants' reactions to subtle changes in caregiver-infant interactions

Gabriela Markova[1] | Trinh Nguyen[1,2]

[1]Faculty of Psychology, University of Vienna, Vienna, Austria

[2]Neuroscience of Perception and Action Lab, Italian Institute of Technology, Rome, Italy

Correspondence
Gabriela Markova, Faculty of Psychology, University of Vienna, Liebiggasse 5, 1010 Vienna, Austria.
Email: gabriela.markova@univie.ac.at

Abstract

The present study examined the role of interpersonal synchrony between mothers and their 4-month-old infants ($N = 40$) in infant responses to a modified interaction where mothers continually looked and verbalised towards but did not engage with their children. During a natural interaction we observed behavioural synchrony and for a subsample of infants ($n = 20$) measured change in their salivary oxytocin from before to after the natural interaction. During the modified interaction we observed infant gaze, positive, and negative affect. We found that higher interpersonal synchrony was related to longer infants' social gaze and shorter displays of negative affect during the modified interaction. Increase in infant oxytocin was also associated with longer gaze, but also longer negative and shorter positive affect during the modified interaction. Our results show that interpersonal synchrony allows infants to notice changes in interactions with others, but also helps them to regulate their emotions during such modified exchanges. These findings thus indicate the importance of synchrony experiences with caregivers for the development of early regulatory capacities.

1 | INTRODUCTION

A vast amount of research impressively demonstrates that very young infants are sensitive to the lack of social communication during the so-called still-face (Tronick et al., 1978), and their responses to these situations predict various outcomes ranging from attachment security to better learning outcomes (see Mesman et al., 2009, for review). However, perturbations of social interactions are rarely as dramatic as suspending all communication. For example, caregivers may look at their infants while speaking to another person on the phone, which results in a communicative situation that is strange yet not unusual for children. Social interactions naturally contain uncertainties and thus hold many possibilities for disruptions and interactive mistakes (e.g., Legerstee & Markova, 2007; Markova & Legerstee, 2006; Mayo & Gordon, 2020). Although these modifications are more subtle, infants are well capable of recognizing them. For example, a series of studies examining mother-infant dyads in a double-video set-up showed that 2-month-old infants became distressed when their mothers were unresponsive while maintaining their general level of communication (i.e., infants see a recording of their mothers during a previous interaction; Murray & Trevarthen, 1985; Nadel et al., 1999). While these results demonstrate that infants easily notice and react to such modified social interactions with their caregivers, we have no clear understanding of the mechanisms that (1) facilitate infants' recognition of and (2) explain their affective responses to such instances. Accordingly, the goal of the present study was to examine infants' reactions to a modified interactive situation, where mothers communicated but did not adjust to their infants' social signals. We expected infants' reactions to be a function of their participation in and learning through regularities during early social exchanges.

It has been argued that early interactional experiences could be formative in the development of sensitivity to natural variations of social exchanges (e.g., Di Paolo et al., 2008). One dyadic mechanism that may be particularly important is infants' active participation in interpersonal synchrony. Interpersonal synchrony reflects an adaptive process by which mothers and infants coordinate their behaviours and is characterised by a repetitive-rhythmic organisation (Leclère et al., 2014). While infants might possess innate abilities (e.g., contingency detection; Gergely & Watson, 1996) to recognize others' social bids to synchronise from birth, starting at 3 months of age they also begin to actively engage in social coordination of behaviours with their caregivers (e.g., Beebe et al., 2010; Feldman, 2007). Early communication is thus a dynamic process where individual actions are continuously modified by the changing actions of the partner (e.g., Fogel, 1993). However, infants do not only experience perfectly synchronised interactions. They also encounter interactive miscoordination that is usually repaired (Tronick, 1989). The constant oscillation between social coordination, miscoordination and interactive repair is an essential characteristic of early human social interactions (Feldman, 2007). Importantly, this interaction structure offers infants opportunities to learn about and from other people's behaviours to form expectations about their social exchanges (e.g., FeldmanHall & Shenhav, 2019; Michael et al., 2016; Reddy et al., 2013).

The argument that infants learn from and through interactive regularities is consistent with the predictive processing framework that has become a prominent model of cognitive neuroscience (Friston, 2010; Hoehl & Bertenthal, 2021). Accordingly, an organism constantly computes the probability of events in the environment based on sensory input and generates appropriate behavioural responses. To minimise prediction errors, the brain must increase the accuracy of its internal predictive models (Clark, 2013; Friston, 2010). Predictive processing has recently received much attention in developmental literature, where authors argue that infants build internal predictive models of their social environment and structure their behaviour and learning by updating these models through active and

perceptual inference (e.g., Hoehl & Bertenthal, 2021; Köster et al., 2020). Infants generate internal predictive models by passively experiencing prediction errors and by actively engaging with their environment to test their predictions. Both active and passive experiences of interpersonal synchrony with others could allow infants to build more precise predictions and thus increase their sensitivity to caregivers' communicative behaviours. This process becomes particularly important in ensuring smooth and coordinated social exchanges. In fact, studies examining these hypotheses in a social-interactive context showed that early in life infants anticipate and adjust to others' actions especially during daily routines which are marked by a regular and predictable structure (e.g., Fantasia et al., 2016; Reddy et al., 2013). Moreover, greater levels of mother-infant synchrony were found to be associated with infants' increased self-regulatory behaviour during the still-face paradigm (e.g., MacLean et al., 2014; Moore & Calkins, 2004), as well as the emergence of self-control (Feldman et al., 1999), and fewer behaviour problems in toddlers (Feldman & Eidelman, 2004). Interpersonal synchrony may thus provide the necessary basis upon which infants develop their regulatory skills (e.g., Fantasia et al., 2014; Raczaszek-Leonardi et al., 2013).

Interestingly, this hypothesis is well-aligned with the recently proposed allostatic model of oxytocin functioning, which is based on the idea that the oxytocin system anticipates changes in the environment and makes appropriate adjustments in the organism to better cope with such changes (Quintana & Guastella, 2020). Accordingly, oxytocin facilitates stability while at the same time allowing flexibility for an organism to cope with changing environments. These functions may especially come into play during complex social interactions (Hansen & Keller, 2021). In fact, research has consistently shown the important role of oxytocin for early interactions between infants and their caregivers. Oxytocin not only promotes and explains variations in parental caregiving behaviours (e.g., Feldman et al., 2010; Gordon et al., 2010; Naber et al., 2010) and infants' social engagement (e.g., Feldman et al., 2010; Weisman et al., 2012), but is also associated with specific aspects of early interactions (e.g., Feldman et al., 2007; Markova & Siposova, 2019). Importantly, studies have shown that highly synchronous interactions are related to an increase in parental as well as infant oxytocin (e.g., Feldman et al., 2010, 2011), suggesting that experiencing interactive regularities is manifested in the oxytocin system. There is also evidence indicating that caregivers' behaviours during a still-face paradigm change with variations in their oxytocin (e.g., intranasal administration, gene expression; Kim et al., 2014; Mehta et al., 2016). However, it remains unclear whether oxytocin – as a biomarker of synchronous social exchanges – could also explain variations in infants' sensitivity and reactivity to changes in their caregivers' communicative behaviours.

While infants are sensitive to changes in social coordination, human interactions naturally contain miscoordinations and infants must not only recognize these changes, but also regulate their affective response to continue smooth social exchanges with their caregivers. The goal of the present study was to examine the role of interpersonal synchrony and oxytocin in infants' reactions to subtle modifications of the reciprocal structure of interactions with their mothers. Based on available evidence showing that from 3 months infants actively coordinate their social behaviour with others (e.g., Beebe et al., 2010), we observed 4-month-old infants and their mothers during a natural and a modified interaction. During the natural interaction, we measured the dyads' spontaneous interpersonal synchrony levels by micro-coding their social behaviours and assessed infant salivary oxytocin before and after the interaction as a measure of their endocrinological reactivity to naturally synchronous interactions with their mothers. During the modified interaction, mothers were instructed to continuously look at and speak to their infants in an adult-directed manner and not reciprocate infants' communicative bids to introduce changes to the reciprocity of their interaction – akin to naturally occurring interactive mistakes. During the modified interaction, we coded infant social gaze as well as negative and positive behaviours. We hypothesised that variations in interpersonal synchrony are associated with variations in infant gaze behaviour and affective reactions during the modified interaction. Specifically, we expected that high levels of interpersonal synchrony during the natural interaction – as reflected in the coordination of infant-caregiver interactive behaviours and possibly by an increase in infant oxytocin – would sensitise infants to changes in the interaction (i.e., longer gaze) and help them bridge these mismatch instances by remaining content (i.e., more positive and less negative behaviours).

2 | METHOD

2.1 | Participants

A total of 40 mothers and their 4-month-old infants ($M = 137.72$ days, $SD = 18.78$ days, 24 girls) participated in the study. Mothers were recruited in prenatal childbirth and mother-infant activity classes. Infants were born full term (min. 36 weeks) and healthy (10-min APGAR score > 9). Mothers in the sample were on average 31 years old ($SD = 3.67$), most were primiparous (90%) and breast-fed their infants (94%). All mother-infant dyads were of European White origin and came from middle-class homes (maternal average years of post-secondary education: $M = 5.56$, $SD = 2.71$), reflecting the demographic composition of the large European university city where this study was conducted. Mothers and infants received a small present for their participation. The Institutional Ethics Committee approved the study.

2.2 | Procedure and material

After arrival at the laboratory, mothers were informed about the procedure and saliva extraction, upon which they signed an informed consent form, and the first salivary sample was collected. Infants were placed in an infant seat that stood on a table ($95 \times 65 \times 50$ cm) and mothers sat facing their infants at eye level from a chair with an approximate distance of 30 cm. Interactions were filmed with two video cameras, one facing the infant and one directed towards the mother. The experimenter was present in the room, out of sight from mothers and infants, and did not communicate with infants or mothers during the procedure (except when explaining the procedure).

Infants were tested when they were calm and alert. Mother-infant dyads were observed during three situations that were presented in a fixed order: Baseline, Natural Interaction, and Modified Interaction (see Figure 1). (1) During the *Baseline* ($M = 587.95$s, $SD = 55.73$s, *range* = 390–720s), no interaction took place between mothers and infants. Infants watched a Baby Einstein® DVD on a computer screen, while mothers completed various questionnaires and were instructed to not engage with their infants. This condition was necessary to control for the various activities of the dyad that may exert an effect on their oxytocin levels (Markova & Siposova, 2019) and thus was not used for behavioural analyses. (2) During the *Natural Interaction* ($M = 375.4$s, $SD = 99.35$s, *range* = 150–533s), mothers were instructed to interact with their infants as they would do at home. This interaction could include touching, talking, and singing, but no toys were provided. (3) During the *Modified Interaction* ($M = 98.64$s, $SD = 41.72$s, *range* = 19.64–199.56s), mothers were instructed to deliver an emotionless speech about facts (e.g., reciting details of her résumé) in an adult-directed manner to their infants, while continually looking at, but refraining from engaging with or reacting to the infant using affective displays, verbalizations, or touch. The modified interaction was followed by other short interactive conditions designed to change the structure of the mother-infant interactions. These conditions were not analysed for the purpose of the present study. We aimed to record 10 min of each situation (or the sum of all modified interactions), but discontinued recording if infants became fussy or upset.

During the visit, a total of four saliva samples were collected from infants in 10-min intervals (e.g., Kim et al., 2014) using oral swabs to determine the concentration of oxytocin (see Figure 1). A research assistant collected the saliva samples by holding one end of a swab specifically designed for infants (Salimetrics Infant's Swab) while the infants
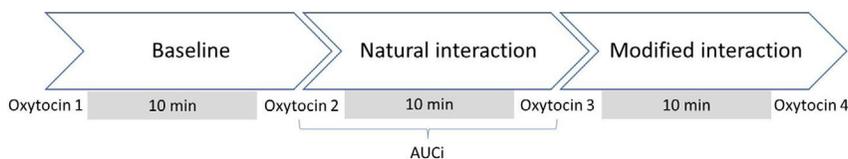

FIGURE 1 Study design.

sucked the other end. The swabs were put into collection tubes and kept on ice in a thermocol ice box during the whole procedure. After the procedure, collection tubes were frozen and stored at −20°C. To attempt to control for potential unknown diurnal effects, visits to the laboratory were scheduled between 1 and 4 pm, at least 1 h after the consumption of food or drinks (other than water), and 30 min after breastfeeding, following previous research (e.g., Feldman et al., 2011). The mean time difference between the last feeding and first saliva collection was $M = 90.94$ min ($SD = 31.24, range = 15$–167 min). One dyad provided the first saliva sample 15 min after breastfeeding. After excluding their data points, the next lowest time difference between the last breastfeeding and the first saliva extraction was 55 min. Because the results did not change when these data points were excluded, we have retained this data in the sample.

2.3 | Measures

2.3.1 | Questionnaires

Mothers completed a demographic questionnaire, providing information about their and their infants' age, education, health history, and feeding style. Additionally, because maternal depression can alter their interactions with infants, mothers were screened for depressive symptoms using the Beck Depression Inventory (BDI-II; Beck et al., 1996). Total scores of 0–13 are in the minimal range, 14–19 are mild, 20–28 are moderate, and 29–63 are severe. All mothers indicated minimal to mild levels of depressive symptoms ($M = 7.48$, $SD = 4.91$), thus we included all dyads in further analyses.

2.3.2 | Behavioural coding

All sessions were videotaped and coded offline using compatible coding software (Mangold Interact, Datavyu). We coded maternal and infant gaze and facial expression during the natural interaction, and infant gaze and facial expression during the modified interaction (Legerstee & Markova, 2007; Markova & Legerstee, 2006). Gaze was coded along two dimensions: (a) social, as directed at the respective interaction partner's face, and (b) away, as gazes away from their partner's face at something else in the surroundings. Gaze away was coded as a mutually exclusive category. Each gaze shift had to last at least 1 s. Positive facial expressions were defined as smiles with the mouth (open or closed) turned upward. Negative facial expressions were coded as displays of negative emotions like distress, fretting, anger, or discontentment with mouth curled or grimacing. Neutral facial expressions were defined by smooth forehead, eyes open, mouth relaxed open/closed, or slightly pursed (Koulomzin et al., 2002). Neutral face was coded as a mutually exclusive category. Each behaviour was coded frame-by-frame and their duration was calculated as a proportion of each condition duration, respectively, to account for individual variations in interaction duration. The behavioural modalities (i.e., gaze, facial expressions) as well as infant and maternal behaviours were coded separately and at different times by two different observers who were blind regarding the hypotheses of the study. To determine inter-rater reliability, one ratter coded all data and a second ratter independently coded 30% of randomly selected data. Sufficiently high inter-rater reliability was achieved for all behavioural measures as indicated by Cohen's kappa: infant gaze $\kappa = .93$, mother gaze $\kappa = .87$, infant facial expressions $\kappa = .78$, mother facial expressions $\kappa = .71$.

2.3.3 | Interpersonal synchrony analysis

Interpersonal synchrony during the natural interaction was estimated using Cross-Recurrence Quantification Analysis (CRQA; Shockley et al., 2002). CRQA can detect behavioural attunement and coordination in non-linear nominal time series and has been increasingly employed in analyses of behavioural patterns (Abney et al., 2015; Nomikou et al., 2016).

To include the behavioural time-series in CRQA, the data were pre-processed. The behavioural time-series, which were coded frame-to-frame at a sampling rate of 25 Hz, were downsampled to 5 Hz for computational efficiency. Behavioural coding at sampling rates of as low as 1 Hz are deemed suitable for synchrony analyses (Beebe et al., 2010). The behavioural time-series were then recoded. Gaze towards the interaction partner was coded as 1, gaze away was coded as 0, and non-codable events were coded as missing (*NaN*) in both time series to exclude them from the analyses. Positive facial expressions were coded as 1, neutral and negative facial expressions were coded as 0, and non-codable events were coded as missing (*NaN*) in both time series.

We calculated four types of interpersonal synchrony. Based on previous research (e.g., Feldman & Eidelman, 2004), we estimated matches in gaze towards the interaction partner (gaze synchrony) and matches in positive affect (affect synchrony). Moreover, because there is a behavioural tendency initiated by social gaze (e.g., Keller et al., 1999) and previous studies have used mixed synchrony categories combining social gaze with affective behaviour in different modalities (e.g., vocalisations, touch; Apter-Levi et al., 2014; Beebe et al., 2010, 2016, 2018; Moore et al., 2016), we included categories where social gaze of one partner was matched with positive affect by the respective other partner (mother gaze-infant affect and infant gaze-mother affect synchrony).

We calculated the recurrence rate as an indicator for interpersonal synchrony. The recurrence rate was estimated in R using the *crqa* function and is the percentage of recurrent points falling within a specified radius (Abney et al., 2015; Coco & Dale, 2014). We set the window size to 3 s and the radius to 1. The window size is consistent with previously reported lags of coordination (Beebe et al., 2010) and the radius was estimated using the *optimizeParam* function.

2.3.4 | Assessment of oxytocin

A standard enzyme immunoassay kit (Oxytocin EIA kit, ADI-901-153, Enzo Life Science) was used to determine the concentration of oxytocin. The limit for detection of the assay was 11.7pg/ml. Saliva was recovered from the swabs by centrifugation ($2500 \times g$ for 10 min at 4°C), and samples were measured without any further modification. All samples were run in duplicates and a separate standard curve was constructed for each plate. The concentrations (in pg/ml) of oxytocin were calculated from the relevant standard curve using Softmax Pro 5.2. Each standard curve was checked for quality control parameters as stated in the instructions. The intra-assay coefficient of variability was 13.28%.

For the purpose of this study, we calculated the change in infant oxytocin with respect to increase in the area under the curve from before to after the natural interaction, because this measure emphasizes the sensitivity of the system and changes over time (Markova & Siposova, 2019; Pruessner et al., 2003). There was a substantial amount of missing oxytocin data (oxytocin before the natural interaction = 41.5%; oxytocin after the natural interaction = 43.9%) that was due to either an insufficient volume of saliva or an error in computing oxytocin (i.e., concentration was below the limit of detection of the assay). Thus, we were only able to collect usable oxytocin data from a subsample of $n = 20$ infants. These infants did not differ from the rest of the sample on any of the demographic variables, dyadic behaviour during the natural interaction, nor infant behaviour during the modified interaction, $p > .404$.

2.4 | Statistical analyses

All statistical analyses were conducted in RStudio (RStudio Team, 2020). We calculated separate regression models for infant gaze, negative and positive facial expressions during the modified interaction. Fixed effects were grouped according to our hypotheses:

dependent variable ~ gaze synchrony + affect synchrony

dependent variable ~ mother gaze-infant affect synchrony + infant gaze-mother affect synchrony

dependent variable ~ oxytocin change

To assess the relation between interpersonal synchrony during the natural interaction and infants' social gaze and positive facial expressions during the modified interaction, we ran a general linear model utilising function *glm* to account for the Poisson distribution of the behavioural count data. The distribution of infants' negative facial

expressions, on the other hand, was left-skewed and zero-inflated. We accounted for this distribution by using a zero-inflated Poisson regression utilising the function *zeroinfl* of package pscl (Zeileis et al., 2008). The reported estimates refer to the count model coefficient. A Vuong test provided evidence for a better model fit of the zero-inflated Poisson regression in a comparison to a general linear regression, $z < -2.700$, $p < .003$. Due to the small sample size of usable oxytocin data, we analysed the relation between infant oxytocin and their behaviours during the modified interaction in separate linear regressions using the function *lm*, which must be taken as exploratory. In addition, we have conducted an a priori power analysis using G*Power (Faul et al., 2009) which showed that, with $n = 20$, we are able to detect medium to large effect sizes.

The following predictor variables were z-transformed (continuous): gaze synchrony, affect synchrony, mother gaze-infant affect synchrony, infant gaze-mother affect synchrony and in a subsequent analysis slope difference of oxytocin change. Estimates and 95% confidence intervals are reported based on standard errors. We tested the overall effect of the predictors by comparing the full model's deviance with that of a null model, comprising only the intercept; this allowed us to establish whether including predictors provided a better fit to the data and avoided type I errors. Multiple comparisons, when needed, were corrected for by using the false discovery rate (Benjamini & Hochberg, 1995).

3 | RESULTS

Descriptive statistics of all variables are provided in Table 1.

3.1 | Natural interaction

We tested the relation between the synchrony variables during the natural interaction using Spearman's rank correlations (see Table 2; see also Table S1 for correlations between maternal and infant individual behaviours during the natural interaction). All reported p-values were corrected for multiple comparisons. Higher gaze synchrony was associated with lower mother gaze-infant affect synchrony, while affect synchrony was positively associated with mother gaze-infant affect synchrony. Gaze, affect and infant gaze-mother affect synchrony were not significantly related, $p = .361$. Next, we examined the relation between individual maternal as well as infant behaviours and the different forms of synchrony. Gaze synchrony was highly correlated with infant gaze towards the mother, $\rho = .995$, $p < .001$, as

TABLE 1 Descriptive statistics for all measures of the present study

Variables	M	SD	Range
Natural interaction			
Affect synchrony*	43.10%	23.10%	0.00–88.01%
Gaze synchrony*	37.49%	22.88%	5.12–86.22%
Mother gaze-infant affect synchrony*	50.81%	21.89%	0.00–93.07%
Infant gaze-mother affect synchrony*	65.95%	38.25%	0.00–99.43%
Infant oxytocin change**	81.87	105.04	−128.89–260.02
Modified interaction (Infant Behaviours)			
Gaze at mother	41.00%	28.30%	0.00–92.00%
Negative facial expressions	19.70%	24.20%	0.00–88.80%
Positive facial expressions	80.30%	24.20%	12.00–100%

Note: * assessed as recurrence rate; ** area under the curve in pg/ml.

TABLE 2 Spearman's rank correlations between gaze synchrony, affect synchrony, mother gaze- infant affect synchrony, infant gaze-mother affect synchrony and oxytocin change

Rho	1.	2.	3.	4.	5.
1. Affect synchrony	1	–	–	–	–
2. Gaze synchrony	−0.15	1	–	–	–
3. Mother gaze-infant affect synchrony	0.55*	−0.34*	1	–	–
4. Infant gaze-mother affect synchrony	0.16	−0.12	0.32+	1	–
5. OT change	−0.40(*)	0.35	−0.19	−0.02	1

Note: *$p < .050$ (corrected); +$p < .099$ (corrected); (*)$p < .050$ (uncorrected).

well as infant positive facial expressions, $\rho = .485$, $p = .024$. Higher mother gaze-infant affect synchrony was associated with lower proportions of infant positive facial expressions, $\rho = −.418$, $p = .048$. All other correlations between synchrony and individual behaviours were not significant, $p > .192$.

Bootstrapped ($n = 1000$) spearman rank correlation analyses revealed that affect synchrony was negatively correlated with infant oxytocin change from before to after the natural interaction (Table 2). All other correlations between infant oxytocin change and other forms of synchrony were not significant, $p > .109$.

3.2 | Modified interaction

Next, we tested the relation between infants' different behaviours during the modified interaction. First, we used a generalised linear model including infant positive facial expressions as the response variable and infant social gaze as a predictor variable; this analysis yielded no significant results, $p = .998$. Second, we used a zero-inflated regression to test infant negative facial expressions as the response variable and infant gaze as the predictor variable. Higher proportions of infant negative facial expressions were related to lower proportions of infant social gaze, *estimate* = −0.005, *SE* = 0.002, *95% CI* = [−0.013 −0.007], $z = −3.37$, $p < .001$.
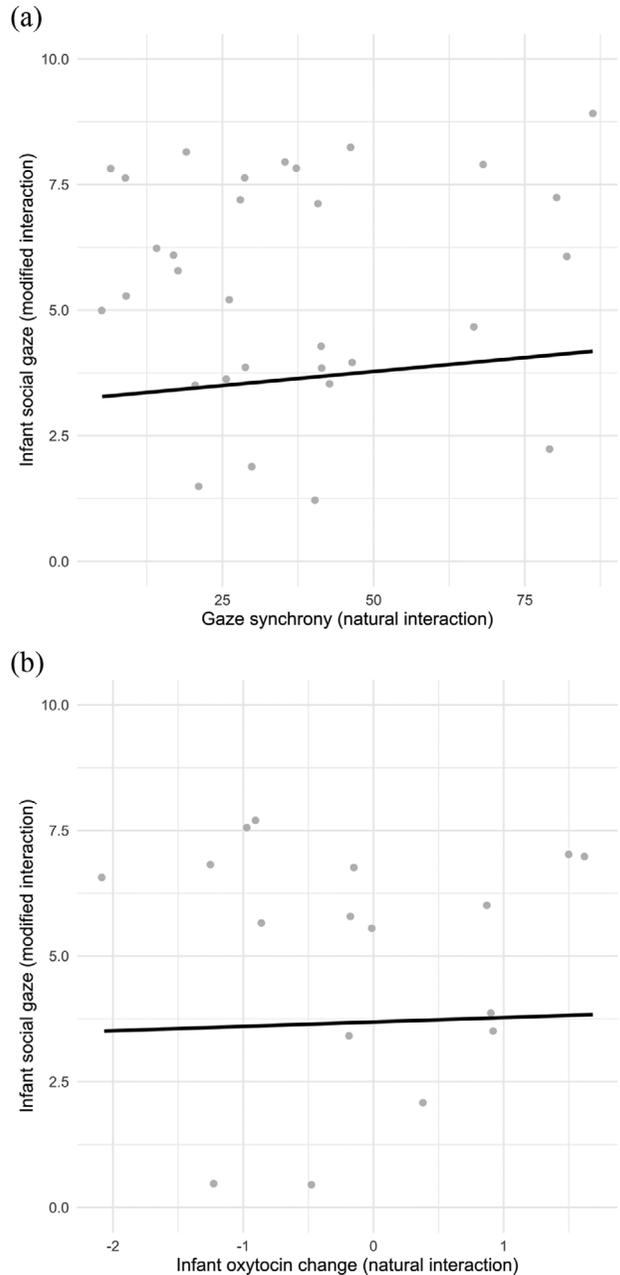
3.3 | Infant social gaze during the modified interaction

We then went to examine our main hypotheses (see Table S2 for model outputs from all models). To answer our first hypothesis, we analysed if higher interpersonal synchrony during the natural reaction was related to increased infant gaze using a generalized linear model. Results showed that higher gaze synchrony was associated with higher proportions of infants' gaze towards their mothers during the modified interaction, *estimate* = .753, *SE* = .078, *95% CI* = [.599.905], $z = 9.63$, $p < .001$ (Figure 2a). Affect synchrony, $p = .169$, nor any form of gaze-affect synchrony, $p > .069$, were not significantly related to infant social gaze during the modified interaction. In a separate generalized linear model, we analysed the association between infant changes in oxytocin from before to after the natural interaction and their social gaze during the modified interaction. Results revealed that infant oxytocin reactivity was positively related to their social gaze, *estimate* = .087, *SE* = .036, *95% CI* = [.017 .158], $z = 2.426$, $p = .015$ (Figure 2b), suggesting that increase in infant oxytocin was related to longer infant gazes at their mothers in the modified interaction condition.

3.4 | Infant positive facial expressions during the modified interaction

For our second hypothesis, we examined whether interpersonal synchrony was related to infants' positive affect in the modified interaction and used generalised linear models to conduct the analyses. We did not find significant

FIGURE 2 Positive relation between (a) Gaze synchrony and (b) Infant oxytocin change during the natural interaction (*x* axes) and infant social gaze during the modified interaction (*y* axes).

associations between neither form of interpersonal synchrony and infants' display of positive facial expressions during the modified interaction, $p > .091$. A separate generalised linear model showed, in contrast, that infants' oxytocin reactivity was negatively related to their positive facial expressions, *estimate* $= -.109$, *SE* $= .025$, *95% CI* $= [-.160\ -.059]$, $z = -4.29$, $p < .001$ (Figure 3), indicating that an increase in infant oxytocin from before to after the natural interaction was associated with shorter positive facial expressions during the modified interaction.
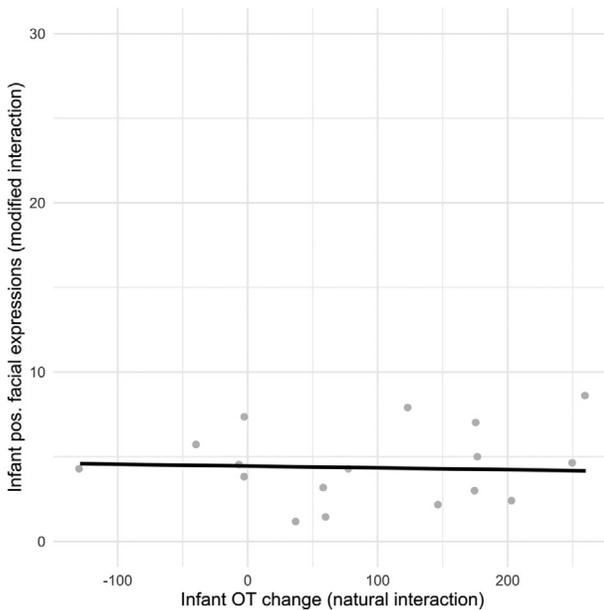
FIGURE 3 Infant oxytocin change during the natural interaction (*x* axis) was negatively related to their positive facial expressions during the modified interaction (*y* axis).

3.5 | Infant negative facial expressions during the modified interaction

For our third hypothesis, we tested whether interpersonal synchrony was related to infants' negative affect in the modified interaction. Zero-inflated regression analyses revealed that infants showed shorter displays of negative facial expressions during the modified interaction with higher gaze synchrony, *estimate* = −.802, *SE* = .131, *95% CI* = [−1.059 −.544], *z* = −6.11, *p* < .001 (Figure 4a), as well as with higher infant gaze-mother affect synchrony, *estimate* = −.005, *SE* = .002, *95% CI* = [−.009 −.002], *z* = −2.567, *p* = .002 (Figure 4b). A separate zero-inflated regression analysis showed that infant oxytocin reactivity was positively associated with infants' negative facial expressions during the modified interaction, *estimate* = .227, *SE* = .055, *95% CI* = [.119 .335], *z* = 4.13, *p* < .001 (Figure 4c), suggesting that when infants showed an increase in oxytocin over the course of the natural interaction, they also displayed longer negatively valanced facial expressions during the modified interactions. In contrast, infants' negative facial expressions were not related to affect synchrony, *p* = .099, nor mother gaze-infant affect synchrony, *p* = .200.

4 | DISCUSSION

In the present study we examined the role of behavioural synchrony during natural interactions of 4-month-old infants with their mothers in shaping their responses during a modified interaction, where mothers did not reciprocate with them. We expected infants' experience of high synchrony to sensitise them to changes in maternal interactive behaviours and allow them to regulate their affective displays during this situation. Confirming these predictions, our results showed that infants who went through highly synchronised interactions with their mothers also showed an increase in their social gaze, indicating sensitivity to changes, as well as a decrease in their display of negative affect, indicating a regulatory effect, when the interaction was modified.

Our first set of findings showed that higher proportions of dyadic gaze synchrony during the natural interaction were related to infant longer social gaze when mothers modified their communicative behaviours. It is possible that previously experienced higher interpersonal synchrony may make infants more socially attentive during non-contingent communication with their mothers. During the modified interaction, mothers were instructed to
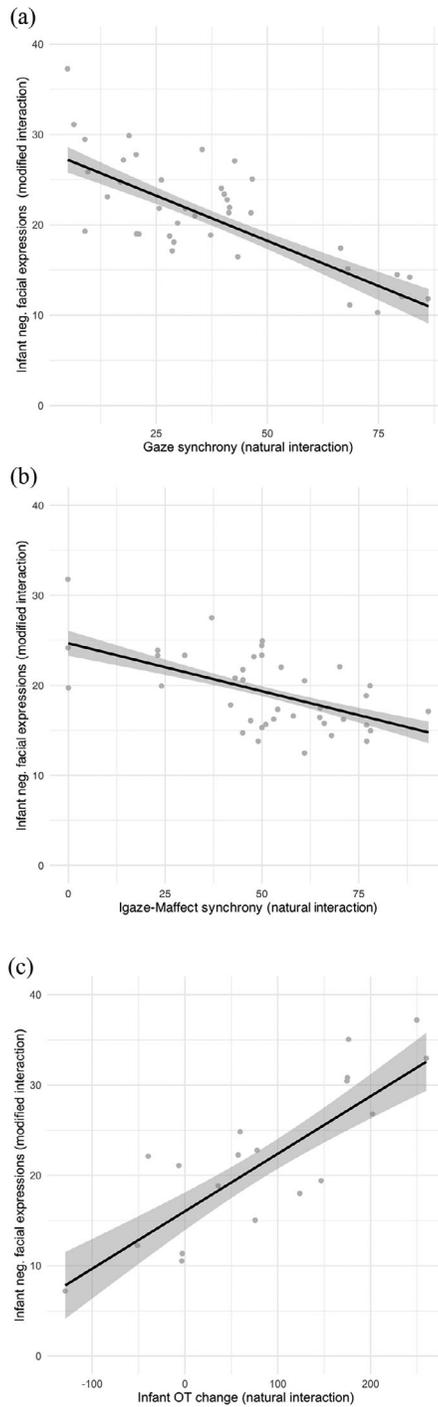
FIGURE 4 (a) Gaze synchrony and (b) Infant gaze-mother affect synchrony during the natural interaction (*x* axes) were negatively associated with infants' negative facial expressions during the modified interaction (*y* axes). (c) Infant oxytocin change during the natural interaction (*x* axis) was positively related to infants' negative facial expressions during the modified interaction (*y* axis).

continuously look at their infant but to not reciprocate infants' behaviour. Mothers were also directed to use mono-tone adult-directed speech. In this context, increased infant social gaze could demonstrate their sensitivity to changes in the interaction – if infants experience high gaze synchrony, then they may be more surprised during atypical interactions. This interpretation is consistent with arguments suggesting that coordinated social gaze has a key role to play in emotion regulation, the sharing of emotional states, and communicative intent (see Abney et al., 2020). By establishing coordinated eye contact, infants try to assess maternal intentions considering their expectation that mutual gaze is a fundamental feature of reciprocal interaction. They may look longer at their mother to make appropriate predictions about her subsequent behaviour as well as to re-initiate interpersonal synchrony. This process is rooted in the predictions that infants make about the social situations they find themselves in based on their interaction history (Beebe et al., 2016; Hoehl & Bertenthal, 2021).

An alternative explanation of the association between gaze synchrony during the natural interaction and infant increased gaze behaviour during the modified interaction could be explained by infants' general predisposition to gaze towards their interaction partner. Within the first months of life, infant gaze and gaze cueing behaviour evolves from detecting another person's focus of attention and decoding affective information into a more complex ability that allows for enriched social communication (e.g., Lavelli & Fogel, 2005; Neath et al., 2013). Studies have also shown that infant social approach behaviours (i.e., social gaze, smiles, non-distress vocalisations) during a still-face episode are associated with maternal contingent responsiveness. When infants notice the relation between their own behaviours and those of their mothers, they become more aware that they can be active agents in instigating social interactions (e.g., Bigelow et al., 2018; Mcquaid et al., 2010). Thus, an increase in social gaze during a modified social situation could be indicative of infants' general approach and openness to initiate communication with the other person.

Importantly, our results also showed that higher gaze synchrony was associated with decreased infant negative facial expressions during the modified interactions. This finding suggests that the level of behavioural synchrony that infants usually experience allows them to regulate themselves in anticipation of interactional repairs. Infants who are accustomed to the natural fluctuation between synchrony and asynchrony during social exchanges could have learned that bouts of asynchrony will eventually be repaired, which would allow them to self-regulate during these asynchronous instances (Calkins & Leerkes, 2004). Indeed, it would make little sense that infants display negative affect during every instance of miscoordination with their caregivers, since this occurs rather frequently: in our sample, we found that dyads spent only between 37% and 66% of their interaction time in synchronised exchanges, supporting previous findings (e.g., Tronick & Gianino, 1986). It may be that the experience of successfully overcoming coordination errors in an interaction facilitates infants' self-regulatory abilities. This interpretation is consistent with existing evidence showing that interpersonal synchrony guides infants' regulatory attempts to reinstate homeostasis during bouts of negative affect (e.g., Nguyen et al., 2021).

Findings of the present study indicate that gaze synchrony, and not affect synchrony, plays an important role for how infants deal with a socially unavailable mother during the modified interaction. Eyes are usually the first impression of a face to be noticed (Bindemann et al., 2009) and they encode important social information like emotional expression, target of attention, and communicative intentions (Baron-Cohen, 1995). From birth, infants show a preference for direct social gaze (Farroni et al., 2002), which activates neural areas associated with processing communicative signals (Grossmann et al., 2008). Thus, early sensitivity to eye contact may serve as a powerful pre-linguistic tool to communicate and connect with the environment, particularly during early face-to-face interactions where infant comprehension of socio-emotional concepts like emotion recognition, perception of others' minds and social coordination is formed (Csibra & Gergely, 2006; Itier & Batty, 2009).

Interestingly, we also found that synchrony across modalities – specifically the match between infant gazes at mother and maternal positive affect – facilitated infants' regulation of their affective responses (i.e., shorter displays of negative affect) during the modified interaction. Coordination between infant social gaze and maternal positive affect can occur either when infants respond by looking at their mothers' positive facial expression, but more often it entails mothers responding to infants' gaze by showing a positive facial expression (e.g., Mcquaid et al., 2010). We can, therefore, assume that this type of synchrony is more often infant initiated than vice versa. When infants

continuously experience maternal positive facial expressions in association with or even as a social consequence to their looking behaviour, infants' self-efficacy starts to build (Mcquaid et al., 2010). Accordingly, infants may become more efficient at self-regulation because they know that they are actively participating in dynamic and reciprocal interactions with others. This interpretation ties up nicely with research suggesting that infants' active experience promotes, for example, their understanding of goal-directed actions (Reddy et al., 2013; Sommerville et al., 2005), development of memory (Sommerville & Hammond, 2007), planning and problem-solving skills (Radziszewska & Rogoff, 1988), and more mature cooperative abilities (e.g., Warneken et al., 2012). Not only is this finding in line with evidence suggesting a crucial role of infant active inference for learning (e.g., Raz & Saxe, 2020), but active engagement with the world has also lasting effects on developmental outcomes, such as coping with stress and self-regulation (e.g., Beeghly & Tronick, 2011). Thus, infants learn through the caregiver's coordinated and contingent responses to their communicative bids that their actions matter.

For a subsample of infants, we examined the association between changes in their oxytocin level from before to after the natural interaction and infants' behaviours during the modified interaction. In line with the allostasis model of oxytocin functioning suggesting that oxytocin facilitates processing changes in the environment (Quintana & Guastella, 2020), we found that the more infants' oxytocin increased over the course of the natural interaction, the longer infants gazed at their mothers during the modified interaction. However, oxytocin increase was also associated with longer negative facial expressions and shorter positive facial expressions during the modified interactions. By showing negative facial expressions, infants communicated their distress instead of tapping into their own regulatory capacities. It could be the case that activation of the oxytocin system increases infants' sensitivity to changes in the interaction structure, thus setting them up for co-regulation by displaying more negative affect (Atzil et al., 2018). This speculative interpretation seems supported by the dissociation between gaze synchrony and oxytocin in our data. Even though we found that both gaze synchrony and infant oxytocin were associated with increase in infant social gaze behaviours upon changes in interactions, only gaze synchrony was also related to less negative affect in infants. Taken together, gaze synchrony and oxytocin reactivity may prepare infants for divergent regulatory processes.

Overall, results of the present study can only be taken as exploratory due to the small as well as homogeneous sample and statistical issues (i.e., collinearity) that prevented us from testing potential interaction effects between changes in infant oxytocin and interpersonal synchrony on infant behaviour during the modified interaction. Moreover, we used a peripheral measure of oxytocin, while the coordination between oxytocin release in the central and peripheral nervous system is not fully understood. Still, several studies find strong correlations between salivary, urinary and plasma samples of the hormone (e.g., Feldman et al., 2011), and given its non-invasive nature, saliva sampling seems to be an appropriate method to assess hormonal changes in young infants. Also, we could not assess changes in oxytocin from before to after the modified interaction, because it was collapsed in a block with other conditions. Because these modified interactions were all relatively short in duration due to ethical considerations, we could not assess fast changes in oxytocin with our sampling method. Consequently, future research needs to address the changes in oxytocin in response to variations in the interactional structure more systematically.

In conclusion, behavioural synchrony provides stable relationship experiences that may not only allow infants to notice changes in interactions, but also help them to regulate themselves during such changes, as well as to actively reinstate familiar interactional structure with their caregivers. Moreover, oxytocin may enable infants to sense changes in regular interaction patterns and prepare them for co-regulation. Nonetheless, it is likely only in combination with synchrony experiences and the caregiver's oxytocin functioning that oxytocin in infants also contributes to the development of self-regulation. Overall, the combined experience of synchronised interactions as well as interactive mistakes and, maybe even more importantly, the repairs thereof may be vital for the development of early regulatory capacities. As caregivers help infants to understand variability in their interactional environment, infants learn to anticipate and bridge those instances by themselves - taking an important step towards emotional independence.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

ETHICS STATEMENT

The conditions of our ethics approval do not permit public archiving of video data. Readers seeking access to the data should contact the lead author Gabriela Markova. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must meet the following conditions to obtain the data: completion of a formal data sharing agreement.

DATA AVAILABILITY STATEMENT

Demographics, behavioural data and R analysis code have been made publicly accessible on OSF: https://osf.io/265rb/?view_only=4293fb741e3c4b9db69354241ee2a00c.

ORCID

Gabriela Markova https://orcid.org/0000-0003-1092-0137

Trinh Nguyen https://orcid.org/0000-0003-0420-2147

References

Abney, D. H., Paxton, A., Dale, R., & Kello, C. T. (2015). Movement dynamics reflect a functional role for weak coupling and role structure in dyadic problem solving. *Cognitive Processing*, *16*(4), 325–332.

Abney, D. H., Suanda, S. H., Smith, L. B., & Yu, C. (2020). What are the building blocks of parent–infant coordinated attention in free-flowing interaction? *Infancy*, *25*(6), 871–887. https://doi.org/10.1111/infa.12365

Apter-Levi, Y., Zagoory-Sharon, O., & Feldman, R. (2014). Oxytocin and vasopressin support distinct configurations of social synchrony. *Brain Research*, *1580*, 124–132. https://doi.org/10.1016/j.brainres.2013.10.052

Atzil, S., Gao, W., Fradkin, I., & Feldman Barrett, L. (2018). Growing a social brain. *Nature Human Behavior*, *2*, 624–636. https://doi.org/10.1038/s41562-018-0384-6

Baron-Cohen, S. (1995). *Mindblindness: An essay on autism and theory of mind*. MIT Press.

Beck, A. T., Steer, R. A., Ball, R., & Ranieri, W. F. (1996). Comparison of Beck Depression Inventories-IA and -II in psychiatric outpatients. *Journal of Personality Assessment*, *67*(3), 588–597.

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*, 3–141. https://doi.org/10.1080/14616730903338985

Beebe, B., Messinger, D., Bahrick, L. E., Margolis, A., Buck, K. A., & Chen, H. (2016). A systems view of mother-infant face-to-face communication. *Developmental Psychology*, *52*(4), 556–571. https://doi.org/10.1037/a0040085

Beebe, B., Myers, M. M., Lee, S. H., Lange, A., Ewing, J., Rubinchik, N., Andrews, H., Austin, J., Hane, A., Margolis, A. E., Hofer, M., Ludwig, R. J., & Welch, M. G. (2018). Family nurture intervention for preterm infants facilitates positive mother-infant face-to-face engagement at four months. *Developmental Psychology*, *54*, 2016–2031. https://doi.org/10.1037/dev0000557

Beeghly, M., & Tronick, E. (2011). Early resilience in the context of parent-infant relationships: A social developmental perspective. *Current Problems in Pediatric and Adolescent Health Care*, *41*, 197–201. https://doi.org/10.1016/j.cppeds.2011.02.005

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, *57*, 289–300. http://www.jstor.org/stable/2346101

Bigelow, A. E., Power, M., Bulmer, M., & Gerrior, K. (2018). The effect of maternal mirroring behavior on infants' early social bidding during the Still-Face task. *Infancy*, *23*, 367–385. https://doi.org/10.1111/infa.12221

Bindemann, M., Scheepers, C., & Burton, A. M. (2009). Viewpoint and center of gravity affect eye movements to human faces. *Journal of Vision*, *9*, 1–16. https://doi.org/10.1167/9.2.7

Calkins, S. D., & Leerkes, E. M. (2004). Early attachment processes and the development of emotional self-regulation. *Handbook of self-regulation: Research, theory, and applications*, pp. 324–339.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*, 181–204. https://doi.org/10.1017/S0140525X12000477

Coco, M. I., & Dale, R. (2014). Cross-recurrence quantification analysis of categorical and continuous time series: An R package. *Frontiers in Psychology*, *5*, 510. https://doi.org/10.3389/fpsyg.2014.00510

Csibra, G., & Gergely, G. (2006). Social learning and social cognition: The case for pedagogy. In Y. Munakata, & M. H. Johnson (Eds.), *Processes of change in brain and cognitive development. Attention and performance, XXI* (pp. 249–274). Oxford University Press.

Di Paolo, E. A., Rohde, M., & Iizuka, H. (2008). Sensitivity to social contingency or stability of interaction? Modelling the dynamics of perceptual crossing. *New Ideas in Psychology*, *26*(2), 278–294. https://doi.org/10.1016/j.newideapsych.2007.07.006

Fantasia, V., De Jaegher, H., & Fasulo, A. (2014). We can work it out: An enactive look at cooperation. *Frontiers in Psychology*, *5*, 874. https://doi.org/10.3389/fpsyg.2014.00874

Fantasia, V., Markova, G., Fasulo, A., Costall, A., & Reddy, V. (2016). Not just being lifted: Infants are sensitive to delay during a pick-up routine. *Frontiers in Psychology*, *6*, 2065. https://doi.org/10.3389/fpsyg.2015.02065

Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences of the United States of Ameria*, *99*, 9602–9605. https://doi.org/10.1073/pnas.152159999

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*, 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Feldman, R. (2007). 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. https://doi.org/10.1111/j.1469-7610.2006.01701.x

Feldman, R., & Eidelman, A. I. (2004). Parent-infant synchrony and the social-emotional development of triplets. *Developmental Psychology*, *40*, 1133–1147. https://psycnet.apa.org/doi/10.1037/0012-1649.40.6.1133

Feldman, R., Gordon, I., Schneiderman, I., Weisman, O., & Zagoory-Sharon, O. (2010). Natural variations in maternal and paternal care are associated with systematic changes in oxytocin following parent–infant contact. *Psychoneuroendocrinology*, *35*(8), 1133–1141. https://doi.org/10.1016/j.psyneuen.2010.01.013

Feldman, R., Gordon, I., & Zagoory-Sharon, O. (2011). Maternal and paternal plasma, salivary, and urinary oxytocin and parent-infant synchrony: Considering stress and affiliation components of human bonding. *Developmental Science*, *14*(4), 752–761. https://doi.org/10.1111/j.1467-7687.2010.01021.x

Feldman, R., Greenbaum, C. W., & Yirmiya, N. (1999). Mother-infant affect synchrony as an antecedent of the emergence of self-control. *Developmental Psychology*, *35*, 223–231. https://psycnet.apa.org/doi/10.1037/0012-1649.35.1.223

Feldman, R., Weller, A., Zagoory-Sharon, O., & Levine, A. (2007). Evidence for a neuroendocrinological foundation of human affiliation plasma oxytocin levels across pregnancy and the postpartum period predict mother-infant bonding. *Psychological Science*, *18*, 965–970. https://doi.org/10.1111/j.1467-9280.2007.02010.x

FeldmanHall, O., & Shenhav, A. (2019). Resolving uncertainty in a social world. *Nature Human Behaviour*, *3*, 426–435. https://doi.org/10.1038/s41562-019-0590-x

Fogel, A. (1993). *Developing through relationships*. University of Chicago Press.

Friston, K. (2010). The free-energy principle: A unified brain theory? *Nature Reviews Neuroscience*, *11*, 127–138. https://doi.org/10.1038/nrn2787

Gergely, G., & Watson, J. S. (1996). The social biofeedback theory of parental affect mirroring: The development of emotional self-awareness and self-control in infancy. *The International Journal of Psychoanalysis*, *77*, 1181–1212.

Gordon, I., Zagoory-Sharon, O., Leckman, J. F., & Feldman, R. (2010). Oxytocin and the development of parenting in humans. *Biological Psychiatry*, *68*, 377–382. https://doi.org/10.1016/j.biopsych.2010.02.005

Grossmann, T., Johnson, M. H., Lloyd-Fox, S., Blasi, A., Deligianni, F., Elwell, C., & Csibra, G. (2008). Early cortical specialization for face-to-face communication in human infants. *Proceedings of the Royal Society B (Biological Sciences)*, *275*, 2803–2811. https://doi.org/10.1098/rspb.2008.0986

Hansen, N. C., & Keller, P. (2021). Oxytocin as an allostatic agent in the social bonding effects of music. *Behavioral and Brain Sciences*, *44*, e75. https://doi.org/10.1017/S0140525X20001235

Hoehl, S., & Bertenthal, B. I. (2021). An Interactionist Perspective on the Development of Coordinated Social Attention. *PsyArXiv*, https://doi.org/10.31234/osf.io/s5tgz

Itier, R. J., & Batty, M. (2009). Neural bases of eye and gaze processing: The core of social cognition. *Neuroscience and Biobehavioral Review*, *33*, 843–863. https://doi.org/10.1016/j.neubiorev.2009.02.004

Keller, H., Lohaus, A., Volker, S., Cappenberg, M., & Chasiotis, A. (1999). Temporal contingency as an independent component of parenting behavior. *Child Development*, *70*, 474–485. https://doi.org/10.1111/1467-8624.00034

Kim, S., Fonagy, P., Koos, O., Dorsett, K., & Strathearn, L. (2014). Maternal oxytocin response predicts mother-to-infant gaze. *Brain Research*, *1580*, 133–142. https://doi.org/10.1016/j.brainres.2013.10.050

Köster, M., Kayhan, E., Langeloh, M., & Hoehl, S. (2020). Making Sense of the World: Infant Learning From a Predictive Processing Perspective. *Perspectives on Psychological Science*, 15(3), 562–571. https://doi.org/10.1177/1745691619895071

Koulomzin, M., Beebe, B., Anderson, S., Jaffe, J., Feldstein, S., & Crown, C. (2002). Infant gaze, head, face and self-touch at 4 months differentiate secure vs. avoidant attachment at 1 year: A microanalytic approach. *Attachment & Human Development*, 4, 3–24. https://doi.org/10.1080/14616730210123120

Lavelli, M., & Fogel, A. (2005). Developmental changes in the relationship between the infant's attention and emotion during early face-to-face communication: The 2-month transition. *Developmental Psychology*, 41(1), 265–280. https://doi.org/10.1037/0012-1649.41.1.265

Leclère, 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), e113571. https://doi.org/10.1371/journal.pone.0113571

Legerstee, M., & Markova, G. (2007). Intentions make a difference: Infant responses to still-face and modified still-face conditions. *Infant Behavior & Development*, 30(2), 232–250. https://doi.org/10.1016/j.infbeh.2007.02.008

MacLean, P. C., Rynes, K. N., Aragón, C., Caprihan, A., Phillips, J. P., & Lowe, J. R. (2014). Mother-infant mutual eye gaze supports emotion regulation in infancy during the Still-Face paradigm. *Infant Behavior & Development*, 37(4), 512–522. https://doi.org/10.1016/j.infbeh.2014.06.008

Markova, G., & Legerstee, M. (2006). Contingency, imitation, and affect sharing: Foundations of infants' social awareness. *Developmental Psychology*, 42(1), 132–141. https://doi.org/10.1037/0012-1649.42.1.132

Markova, G., & Siposova, B. (2019). The role of oxytocin in early mother-infant interactions: Variations in maternal affect attunement. *Infant Behavior & Development*, 55, 58–68. https://doi.org/10.1016/j.infbeh.2019.03.003

Mayo, O., & Gordon, I. (2020). In and out of synchrony—Behavioral and physiological dynamics of dyadic interpersonal coordination. *Psychophysiology*, 57(6), e13574. https://doi.org/10.1111/psyp.13574

Mcquaid, N., Bibok, M. B., & Carpendale, J. I. M. (2010). Relation between maternal contingent responsiveness and infant social expectations. *Infancy*, 14, 390–401. https://doi.org/10.1080/15250000902839955

Mehta, D., Eapen, V., Kohlhoff, J., Diaz, A. M., Barnett, B., Silove, D., & Dadds, M. R. (2016). Genetic regulation of maternal oxytocin response and its influences on maternal behavior. Neural Plasticity, 2016, Article ID 5740365. https://doi.org/10.1155/2016/5740365

Mesman, J., van IJzendoorn, M. H., & Bakermans-Kranenburg, M. J. (2009). The many faces of the Still-Face Paradigm: A review and meta-analysis. *Developmental Review*, 29(2), 120–162. https://doi.org/10.1016/j.dr.2009.02.001

Michael, J., Sebanz, N., & Knoblich, G. (2016). The sense of commitment: A minimal approach. *Frontiers in Psychology*, 6, 1968. https://doi.org/10.3389/fpsyg.2015.01968

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. https://doi.org/10.1037/0012-1649.40.6.1068

Moore, G., A, Q., K, M., Voegtline, K. M., & DiPietro, J. A. (2016). Don't worry, be (moderately) happy: Mothers' anxiety and positivity during pregnancy independently predict lower mother-infant synchrony. *Infant Behavior and Development*, 42, 60–68. https://doi.org/10.1016/j.infbeh.2015.11.002

Murray, L., & Trevarthen, C. (1985). Emotional regulation of interactions between 2-month-olds and their mothers. In T. M. Field & N. A. Fox (Eds.), *Social perception in infants* (pp. 101–125). Ablex Publishers.

Naber, F., Van IJzendoorn, M. H., Deschamps, P., Van Engeland, H., & Bakermans-Kranenburg, M. J. (2010). Intranasal oxytocin increases fathers' observed responsiveness during play with their children: A double-blind within-subject experiment. *Psychoneuroendocrinology*, 35, 1583–1586. https://doi.org/10.1016/j.psyneuen.2010.04.007

Nadel, J., Carchon, I., Kervella, C., Marcelli, D., & Réserbat-Plantey, D. (1999). Expectancies for social contingency in 2-month-olds. *Developmental Science*, 2(2), 164–173. https://doi.org/10.1111/1467-7687.00065

Neath, K., Nilsen, E. S., Gittsovich, K., & Itier, R. J. (2013). Attention orienting by gaze and facial expressions across development. *Emotion (Washington, D.C.)*, 13(3), 397–408. https://doi.org/10.1037/a0030463

Nguyen, T., Abney, D. H., Salamander, D., Bertenthal, B., & Hoehl, S. (2021). Social Touch is associated with Neural but not Physiological Synchrony in Naturalistic Mother-Infant Interactions. *Neuroimage*, 244, 118599. https://doi.org/10.1016/j.neuroimage.2021.118599

Nomikou, I., Leonardi, G., Rohlfing, K. J., & Rączaszek-Leonardi, J. (2016). Constructing interaction: The development of gaze dynamics. *Infant and Child Development*, 25, 277–295. https://doi.org/10.1002/icd.1975

Pruessner, J. C., Kirschbaum, C., Meinlschmid, G., & Hellhammer, D. H. (2003). Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. *Psychoneuroendocrinology*, 28, 916–931. https://doi.org/10.1016/S0306-4530(02)00108-7

Quintana, D. S., & Guastella, A. J. (2020). An Allostatic Theory of Oxytocin. *Trends in Cognitive Sciences*, 24, 515–528. https://doi.org/10.1016/j.tics.2020.03.008

Raczaszek-Leonardi, J., Nomikou, I., & Rohlfing, K. J. (2013). Young children's dialogical actions: The beginnings of purposeful intersubjectivity. *IEEE Transaction on Autonomous Mental Development*, 5, 210–221. https://doi.org/10.1109/TAMD.2013.2273258

Radziszewska, B., & Rogoff, B. (1988). Influence of adult and peer collaborators on children's planning skills. *Developmental Psychology*, *24*, 840–848. https://psycnet.apa.org/doi/10.1037/0012-1649.24.6.840

Raz, G., & Saxe, R. (2020). Learning in infancy is active, endogenously motivated, and depends on the prefrontal cortices. *Annual Review of Developmental Psychology*, *2*, 247–268. https://doi.org/10.1146/annurev-devpsych-121318-084841

Reddy, V., Markova, G., & Wallot, S. (2013). Anticipatory adjustments to being picked up in infancy. *Plos One*, *8*(6), e65289. https://doi.org/10.1371/journal.pone.0065289

RStudio Team (2020). *RStudio: Integrated development for R*. RStudio. http://www.rstudio.com/

Shockley, K., Butwill, M., Zbilut, J. P., & Webber, C. L. (2002). Cross recurrence quantification of coupled oscillators. *Physics Letters A*, *305*, 59–69. https://doi.org/10.1016/S0375-9601(02)01411-1

Sommerville, J. A., & Hammond, A. J. (2007). Treating another's actions as one's own: Children's memory of and learning from joint activity. *Developmental Psychology*, *43*, 1003–1018. https://psycnet.apa.org/doi/10.1037/0012-1649.43.4.1003

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition*, *96*, B1–11. https://doi.org/10.1016/j.cognition.2004.07.004

Tronick, E. Z. (1989). Emotions and emotional communication in infants. *American Psychologist*, *44*, 112–126. https://doi.org/10.1037//0003-066x.44.2.112

Tronick, E., Als, H., Adamson, L., Wise, S., & Brazelton, T. B. (1978). The infant's response to entrapment between contradictory messages in face-to-face interaction. *Journal of the American Academy of Child Psychiatry*, *17*, 1–13. https://doi.org/10.1016/S0002-7138(09)62273-1

Tronick, E. Z., & Gianino, A. (1986). Interactive mismatch and repair: Challenges to the coping infant. *Zero to Three*, *6*, 1–6.

Warneken, F., Gräfenhain, M., & Tomasello, M. (2012). Collaborative partner or social tool? New evidence for young children's understanding of joint intentions in collaborative activities. *Developmental Science*, *15*, 54–61. https://doi.org/10.1111/j.1467-7687.2011.01107.x

Weisman, O., Zagoory-Sharon, O., & Feldman, R. (2012). Oxytocin administration to parent enhances infant physiological and behavioral readiness for social engagement. *Biological Psychiatry*, *72*, 982–989. https://doi.org/10.1016/j.biopsych.2012.06.011

Zeileis, A., Kleiber, C., & Jackman, S. (2008). Regression models for count data in R. *Journal of Statistical Software*, *27*, 1–25.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.