Synchrony and Specificity in the Maternal and the Paternal Brain: Relations to Oxytocin and Vasopressin

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Objective: Research on the neurobiology of parenting has defined *biobehavioral synchrony*, the coordination of biological and behavioral responses between parent and child, as a central process underpinning mammalian bond formation. Bi-parental rearing, typically observed in monogamous species, is similarly thought to draw on mechanisms of mother–father synchrony. **Method:** We examined synchrony in mothers' and fathers' brain response to ecologically valid infant cues. Thirty mothers and fathers, comprising 15 couples parenting 4- to 6-month-old infants, were visited at home, and infant play was videotaped. Parents then underwent functional magnetic resonance imaging scanning while observing own-infant compared with standard-infant videos. Coordination in brain response between mothers and fathers was assessed using a voxel-by-voxel algorithm, and gender-specific activations were also tested. Plasma oxytocin and arginine vasopressin, neuropeptides implicated in female and male bonding, were examined as correlates. **Results:** Online coordination in maternal and paternal brain activations emerged in social–cognitive networks implicated in empathy and social cognition. Mothers showed higher amygdala activations and correlations between amygdala response and oxytocin. Fathers showed greater activations in social–cognitive circuits, which correlated with vasopressin. **Conclusions:** Parents coordinate online activity in social–cognitive networks that support intuitive understanding of infant signals and planning of adequate caregiving, whereas motivational–limbic activations may be gender specific. Although preliminary, these findings demonstrate synchrony in the brain response of two individuals within an attachment relationship, and may suggest that human attachment develops within the matrix of biological attunement and brain-to-brain synchrony between attachment partners. J. Am. Acad. Child Adolesc. Psychiatry, 2012;51(8):798–811. **Key words:** neuroimaging, parental brain, oxytocin, vasopressin, intersubject correlation

Bio-behavioral synchrony, the coordination of biological and behavioral signals between parent and child, has been described as a central process underlying the formation of mammalian bonding.[1] For instance, the amount of female rats' parenting behavior was found to shape the receptor distribution of their offspring's oxytocin (OT), a nine–amino acid neuropeptide synthesized in the hypothalamus that plays a key role in socialization and affiliation throughout life. Human mothers and infants similarly coordinate biology and behavior. For example, mothers and infants were found to synchronize their heart rhythms online during social interactions, and the extent of such biological coupling was determined by the degree of interactive synchrony between mother and child.[3] Similarly, mothers who engaged in more synchronous interactions showed more coherent activations of the amygdala and nucleus accumbens (NAcc) to their infant's stimuli, and these activations correlated with maternal plasma OT.[4] In addition, synchrony has been found between mothers' and fathers' physiological and behavioral response in the context of infant cues. Following triadic interactions between parents and their 6-month-old infants, maternal and paternal

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plasma OT was found to be interrelated and correlated with the degree of affect synchrony between parents. Such mother–father synchrony is thought to underpin the evolution of family units in mammals,[5] to facilitate the emergence of co-parenting, and to consolidate the mother–father attachment in the context of family formation.[2]

Becoming a parent involves a major neurohormonal reorganization that prepares for the expression of adequate caregiving.[6] Across mammalian species, pregnancy and childbirth are associated with marked changes in maternal brain areas implicated in motivation, nurturance, and attention.[6] Research in bi-parental species points to similar alterations in fathers' brains, contingent upon exposure to infant cues.[7] In humans, imaging studies suggest the involvement of two global networks underlying maternal care, a motivational–emotional limbic network that includes the amygdala, NAcc, and anterior-cingulate cortex (ACC), and a social-attention network implicated in social cognition and empathy, including the medial-prefrontal-cortex (mPFC), superior-temporal-gyrus (STG), insula, inferior-parietal lobule (IPL), and inferior-frontal gyrus (IFG).[4,8-10] This social-cognition and emotional-modulation circuitry underlies the parent's ability to read the infant's nonverbal signals and to provide synchronous parenting. However, because little research has addressed the neurobiology of human fatherhood, it is unclear whether fathering involves similar integration of limbic and cortical networks and is mediated by processes related to pair bonding as in other biparental mammals. Of particular interest is whether brain mechanisms related to mother–father synchrony support the development of fatherhood, a question that bears important implications for the study of human attachment.

From an evolutionary perspective, the maternal and paternal roles are distinct,[6] yet they may share underlying physiological mechanisms.[11] Paternal care is observed in 3% to 5% of mammalian species, and these species are notably monogamous,[12] suggesting that pair-bonding supports the development of mammalian fathering. Animal monogamy is the result of co-evolution of mothering and fathering expressed in facultative fathering, i.e., paternal care that increases infant endurance in the context of mothering.[13] Human paternal investment contributes to children's cognitive, social, and emotional development,[14] whereas father absence increases psychopathology and antisocial conduct.[15,16] Taken together, these findings suggest that the development of co-parenting may be supported by bio-behavioral mechanisms through which parents synchronize their efforts to jointly raise their child.

In addition to brain areas that may show mother–father synchrony, neurohormonal changes during pregnancy, parturition, and lactation may result in distinct profiles of brain activations in mothers and fathers.[17] Brain and behavioral systems undergo changes with motherhood, particularly those implicated in motivation and vigilance.[6] An increase in gray matter volume in the prefrontal cortex, parietal lobe, and midbrain was found in mothers during the postpartum period,[17] suggesting that activations in motivational systems may be more pronounced in mothers. Studies on postpartum maternal motivation in rats differentiate early from late-onset motivation. Hormonal events associated with parturition initially activate neural circuitry implicated in maternal immediate responsiveness to pups, possibly through neural connectivity to motivational–dopaminergic brain areas, such as the NAcc,[17] and human research similarly pointed to the centrality of mesolimbic dopamine/reward pathways for mothering.[18,19] Thereafter, continued sensory experiences through mother–pup interactions establish long-term maternal responsiveness. Late post-partum motivation for infant care requires learning and memory and involves functional reorganization of brain structures and their connections.[20] It is possible that the unconditional maternal motivation initiated by the biology of pregnancy would be more pronounced in mothers, expressed in greater motivation–limbic activations. The later, learning-based care may be shared by mothers and fathers, leading not only to comparable responsiveness in social–cognitive networks but a possible synchrony of such activations based on the parents' growing experience in co-parenting their child.

Both OT and arginine vasopressin (AVP) are neuropeptides that support mammalian social behavior in females and males[21]; yet research indicates dimorphism in their effects on social, affiliative, and sexual behavior.[22] OT has been linked with maternal–infant bonding,[1,2,10] whereas AVP has been associated with male bonding by increasing aggressive and territorial behavior.[22,23] AVP is thought to underlie mammalian fathering by increasing vigilance to selective protection.[24] Recent studies assessing OT and AVP in relation to brain activations showed that whereas maternal

OT levels correlated with left NAcc and right amygdala response to infant cues,[4] intranasal AVP increased men's response in left temporo-parietal junction (TPJ), a key theory-of-mind node.[25] These studies indicate that AVP may modulate social-emotional responses at the cortical level, particularly circuits related to emotional regulation and social cognition, whereas OT may be more closely linked with motivational–limbic structures.[22]

In the current study, we examined whether mothers and fathers would synchronize their brain responses to own-infant cues. Mothers and fathers underwent functional magnetic resonance imaging (fMRI) scanning while observing videos of their infant's solitary play, and the degree of coordination in their brain reactivity was assessed. As we are aware of no study assessing the time-locked coordination of brain activations among attachment partners, such findings, albeit preliminary, may have significant implication for the study of human attachment. Consistent with research on the co-evolution of mothering and fathering, we expected that brain areas implicated in empathy and social cognition, which are based on representing the other's state within one's physiology, will synchronize between the maternal and paternal brains. However, the strong effects of childbirth on motivational structures, including the amygdala and NAcc, were expected to result in higher activations of these structures among mothers. In addition, we tested correlations between plasma AVP and OT with activations in key parenting areas. AVP was hypothesized to correlate with paternal brain activations, whereas OT correlated with the maternal brain. By assessing both brain synchrony and network specificity and their neurohormonal correlates, we hoped to shed further light on the biobehavioral processes underlying the development of co-parenting in humans.

METHOD

Participants

Thirty parents (15 married couples) of 4- to 6-month-old, singleton, full-term infants participated, including seven first-time and 12 veteran parents (12 breast-feeding mothers). Thus, this study addressed the first stages of parental bonding, not the transition to parenthood. Participants were 22 through 37 years old (mean = 29.3, SD = 3.45), had completed 12 to 21 years of education (mean = 15.76, SD = 1.85), and had no history of major physical or mental illness. Parents were recruited through advertisement in the community. Data from some mothers, but not fathers, were also included in a previous report.[4] The study was approved by the Tel-Aviv Sourasky Medical Center Institutional Review Board, and all participants signed informed consent.

Procedure

The study included three sessions. In the first session, families were visited at home when the infant was 4 to 6 months old and were videotaped. Films were used as fMRI stimuli and included mother–infant and father–infant interactions and infant solitary play, each lasting 2 minutes. In the second session, several days after the home visit, each parent underwent brain scanning. Blood samples were collected on a third visit, to avoid the potential impact of blood draw on brain response or vice versa, and this decision is supported by the high individual stability in plasma neuropeptide levels over several months.[26]

fMRI Paradigm

The fMRI paradigm was individually tailored and included eight consecutive, 2-minute, infant-related videos with rest between stimuli. The various clips included vignettes of own infant during solitary play and unfamiliar-infant during solitary play standard across participants, and these two vignettes were used in the current report. Parents also viewed clips of own and standard parent–infant interactions. Stimuli order was counterbalanced and presented in five different orders across participants. Clips were previewed by rest with fixation period of 1 minute. Rest with fixation periods of 15 to 18 seconds was presented between films. All infant videos were micro-coded for infant affective state on a computerized system (Noldus, Wageningen, the Netherlands) using a validated coding scheme by trained coders to ensure that infant state did not differ between own-infant and standard-infant videos. In all films, infants were in neutral or positive affective states. The stimulus presented in the own-infant condition was individually tailored for each couple, and the group analyses combines 15 different infant films as one own-infant condition. It is thus assumed that brain responses to the own-infant in parents, at a group level, are beyond the infant's specific state.

fMRI Acquisition

Imaging was performed on a GE-3T Sigma Horizon echo-speed scanner with a resonant gradient echoplanar imaging system. Functional images were acquired using a single-shot echo-planar T2*-weighted sequence. The following parameters were used: 128 × 128 matrix; field-of-view of 20 × 20 cm; 39 slices with 3-mm thickness and no gap. TR/TE 3000/35; flip angle 90°, acquisition orientation of the fourth ventricle plane. In addition, each functional scan was accompanied by a three-dimensional (3D) anatomical scan using anatomical 3D sequence spoiled gradient (SPGR) echo sequences that were obtained with high-resolution of 1 × 1 × 1 mm.

fMRI Preprocessing and Analyses

BrainVoyager QX version 2.1 was used to analyze fMRI data. The first six functional volumes, before signal stabilization, were excluded from analysis.

Preprocessing

3D motion correction was conducted, using trilinear interpolation, linear trend removal, and high-pass filtering. A 4-mm, full-width at half maximum Gaussian smoothing was used to overcome differences in intersubject localization. Functional maps were manually coregistered with $1 \times 1 \times 1$ triliniar-interpolated anatomical maps, which were normalized into Talairach space. Three-dimensional first-level statistical parametric maps were calculated separately for each subject using a generalized linear model (GLM) in which all stimuli conditions were positive predictors with a hemodynamic lag of 6 seconds. For second-level analyses, we used a statistical threshold of $p < .007$ and a voxelwise extent threshold of $\kappa = 3$ functional voxels ($3 \times 27\text{mm}^3 = 81\text{mm}^3$) to identify significant clusters. The threshold was determined a priori based on our previous work[4] and was designed for a preliminary exploratory investigation. We attempted to optimize the ratio between type I and type II errors,[27] while considering that our natural stimuli may be a source of intergroup variance.

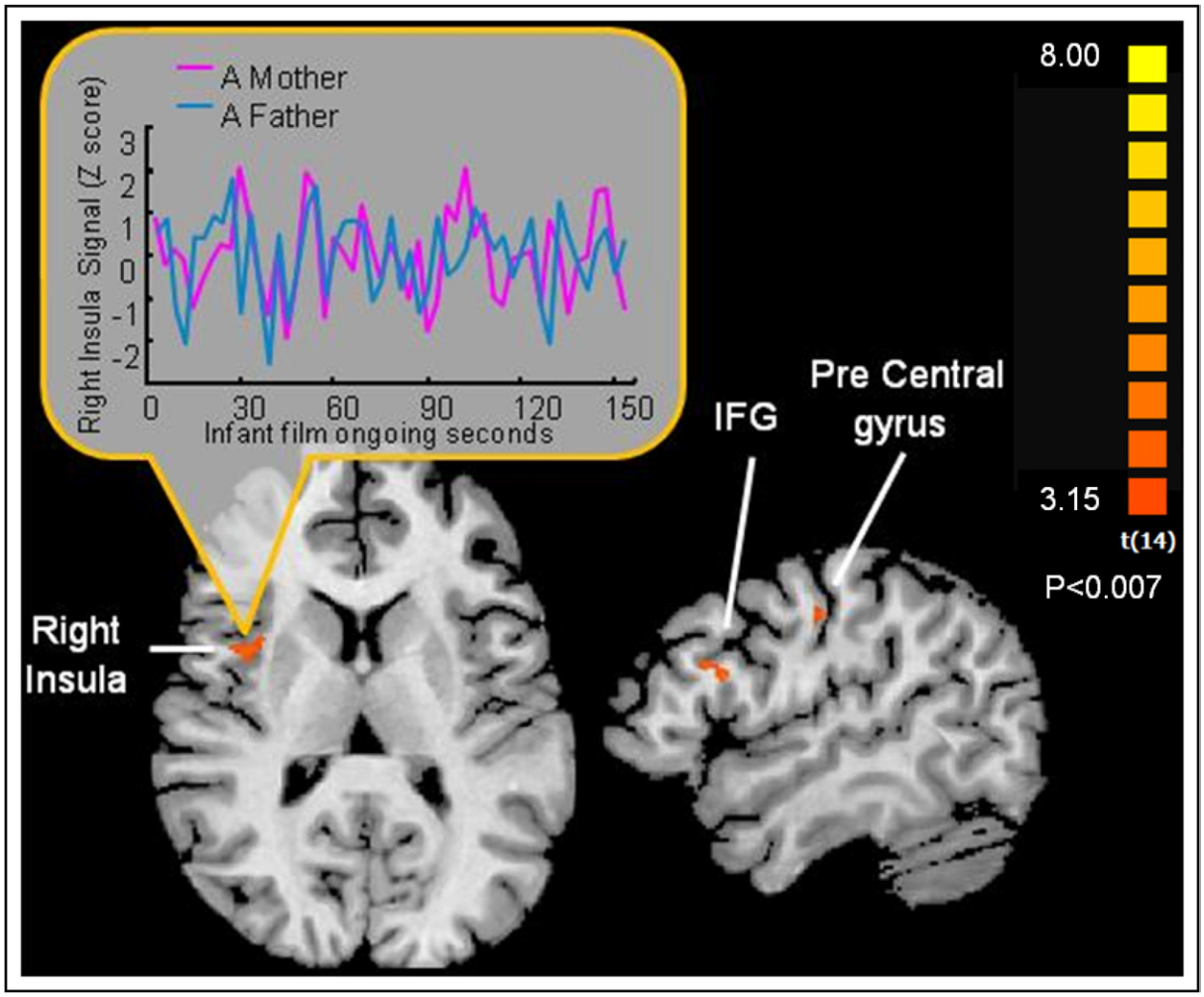
Analyses

Whole-Brain Intercouple Correlations. We evaluated the parental brain response by using a BOLD-fMRI–based analysis that tracked the voxel-by-voxel synchronization between mothers' and fathers' brains across the 2-minute video of own-infant. To search for brain regions that would work synchronously across the film,[28] we developed an algorithm that first transformed all brains to Talairach space and then preformed a voxel-by-voxel Pearson correlation between the mother's and father's brains during observation of same clip, resulting in 15 correlation values for each voxel, one for each couple. A cross-subject brain synchrony analysis was conducted by Hasson et al.[28]; however, unlike their study, in which all subjects watched the same film, our correlation scope addressed the intercouple matrix, the focus of this research. The correlation was computed for the voxel signals of each mother and father of the same infant. The matrices included 51 time-points of voxel signal for each parent (120-second film proceeded and followed by 15- and 18-second rest periods, TR = 3), and yielded a single r value per voxel. We then normalized these correlations using a Fisher z transformation and assessed whether the 15 samples had a mean correlation value that was significantly greater (or smaller) than 0 using the t test. To evaluate the brain areas that correlates specifically to the own-infant film and not to infants in general, we conducted the same procedure (i.e., 15 whole-brain correlations and t tests) for the standard-infant control film and subtracted the standard-infant multi-subject correlation map from the own-infant multi-subject correlation map in a second-level t test of normalized correlation values. The test revealed the brain areas that were differentially correlated in the mother's and father's brain response specifically to their own infant at the level of the group. We refer to such intersubject correlation as "mother–father synchrony," a term addressing the coordinated changes in BOLD signals in specific brain areas in mother's and father's brain in relation to the same infant. The intersubject correlation measures coordinated changes of activation in two brains summed across the film (yielding the r value for each voxel of each pair of subjects).

Whole-Brain GLM. A second-level, multi-subject, repeated-measures GLM was computed for mothers and fathers, in which the various infant-related films were defined as distinct block predictors. Total number of blocks included two "own stimuli" (own infant, own parent–infant interaction) and four control stimuli (two unfamiliar infant films, two unfamiliar mother–infant interaction, and additional gender-related parent–infant interaction, male for fathers, female for mothers). A 2×2 analysis of variance (ANOVA) was conducted for all subjects and all conditions ($F_{8,224}$, $p = 2\times10^{-14}$). A "between-subjects factor" contained two levels (mothers>fathers), and a "within-subject factor" contained two levels (own-infant>standard infant). To evaluate the differences between mothers and fathers, a second-level post hoc contrast was calculated.

Hormonal Analysis. Blood was drawn from the antecubital vein of the parents into 9-mL, chilled Vacuette tubes (Grenier Bio-One, Kresmunster, Austria) containing lithium–heparin supplemented with 400 KIU of Trasylol (Bayer, Leverkusen, Germany) per 1 mL of blood. Samples were kept ice chilled for up to 2 hours before centrifugation at 1,000 g for 15 minutes at 4°C. Supernatants were collected and stored at −70°C until assayed. Parents were asked to refrain from food intake 30 minutes before blood draw. Maternal blood was drawn at least 30 minutes after nursing and 30 minutes before nursing. OT and AVP assays were available for 13 mothers and 11 fathers. Previous studies[2,26] showed no differences between plasma OT levels in breast-feeding and non–breast-feeding mothers when OT was not measured around breast-feeding. Determinations of hormones were performed using a commercial OT and AVP enzyme-linked-immunosorbent assay kit (Assay Design, Ann Arbor, MI), as described in earlier studies.[2,29] Measurements were performed in duplicate, and the concentrations of samples were calculated by MATLAB-7 (MathWorks, Natick, MA) according to relevant standard curves. The intra-assay and interassay coefficients for OT were less than 7% and 15.8%, respectively. The intra-assay

FIGURE 1 Mother–father brain synchronization during observation of own-infant video. Note: Brain areas that show interparent correlations among 15 fathers and 15 mothers in response to their own-infant video include visual cortex, pre-motor and motor cortices, cerebellum, inferior-parietal-lobule (IPL), inferior frontal gyrus (IFG), and insula. X = 47, Z = 12.



and interassay coefficients for AVP were less than 3.9% and 16.9%, respectively.

Whole-Brain Hormone Correlations

These analyses examined which brain areas selective to the own-infant>standard-infant contrast correlate with plasma OT and AVP. We used whole-brain analysis of covariance (ANCOVA) with each hormone plasma levels as covariates, separately for fathers and mothers.

Region-of-Interest Analysis

The region-of-interest (ROI) analysis was conducted using the right amygdala. This region was selected based on previous research that marks the maternal right amygdala as a limbic structure responding to the own-infant contrast in relation to caregiving.[4,30] In addition, the right amygdala differentiated between mothers and fathers and was defined from the ANOVA (in the contrast mothers versus fathers × own versus unfamiliar infant) as a functional ROI. The ROI included 108 voxels, peak activation in Talairach coordinates: X = 15, Y = −2, Z = −12, t = 3.456168, p = .001289. Mean GLM β values of the 108 voxels in the contrast own-infant>standard-infant was then correlated to OT and AVP.

RESULTS

Synchrony and Specificity in Mothers' and Fathers' Brains: Whole-brain Intersubject Correlations

Figure 1 and Table 1 present brain areas that showed concurrent activations in mothers and

TABLE 1 Brain Areas Showing Correlations Between Mothers' and Fathers' Brain Response During Presentation of Own-Infant Video

	Peak X	Peak Y	Peak Z	BA	t	*p*	K
Left lingual gyrus	−15	−91	1	17	8.987	.000	132
Left lentiform nucleus	−18	5	1		6.866	.000	210
Right occipital gyrus	6	−91	28	19	6.642	.000	176
Right cerebellum	3	−43	−29		6.485	.000	203
Left dorsal ACC	−9	23	31	32	6.451	.000	93
Right pre-central gyrus	54	−4	46	4	6.372	.000	106
Right IFG	48	11	22	44	6.063	.000	48
Right posterior cingulate	12	−37	19	23	6.032	.000	106
Right cuneus	18	−88	37	19	5.914	.000	133
Left IPL	−42	−55	34	40	5.814	.000	267
Left IPL	−63	−40	37	40	5.664	.000	93
Right pre-central gyrus	42	−16	46	4	5.395	.000	208
Left middle frontal gyrus	−45	2	49	6	5.287	.000	147
Right dlPFC	48	44	16	46	5.216	.000	322
Right middle temporal gyrus	63	−46	−5	21	5.174	.000	86
Right IFG	27	17	−8	47	5.150	.000	213
Right insula	33	5	13	13	5.100	.000	157
Left superior parietal lobule	−39	−58	58	7	5.037	.000	123
Right dmPFC	3	38	28	9	4.965	.000	375
Left superior frontal gyrus	−12	20	49	6	4.873	.000	92
Right IPL	60	−31	22	40	4.670	.000	83
Right superior frontal gyrus	15	38	43	8	4.380	.001	117
Left middle frontal gyrus	−18	53	10	10	4.158	.001	112

Note: Mother–father correlation analysis. X, Y, Z represent Talairach coordinates. N = 30 subjects, 15 pairs. Cluster size threshold > 3. Confidence threshold min = 4.15. K = number of voxels in significant cluster; ACC = anterior cingulate cortex; BA = Brodmann area; dlPFC = dorso-lateral pre-frontal cortex; dmPFC = dorso-medial pre-frontal cortex; IFG = inferior frontal Gyrus; IPL = inferior parietal lobule.

fathers during observation of own-infant solitary play. Results demonstrate synchrony between mothers' and fathers' brains in associative visual cortex, lentiform nucleus, cerebellum, ACC, premotor and motor cortices, IFG, cuneus, IPL, medial and lateral prefrontal cortex (PFC), temporal cortex, and insula when responding to their infant.

Whole-Brain GLM

Figure 2 and Table 2 present differences between mothers' and fathers' brains activations when responding to their infant in the contrast own infant>standard infant. As seen, mothers showed higher activations in the right superior temporal gyrus, right post-central gyrus, right fusiform, right amygdala, right lentiform nucleus, right temporal pole, and right caudate. Fathers showed higher activations in superior-occipital and temporal gyri, the left medial PFC, left precuneus, and left inferior parietal gyri.

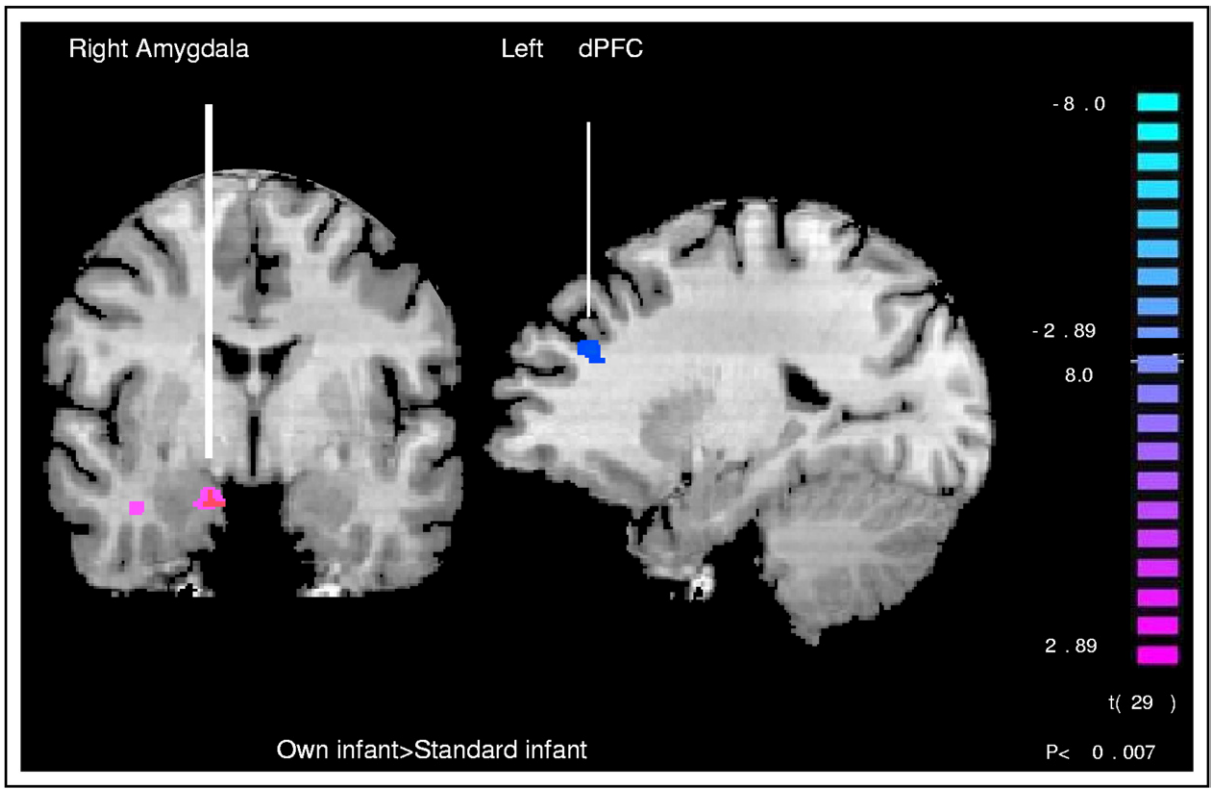
Oxytocin and Vasopressin. Consistent with previous studies,[2,26] no mean-level differences in plasma OT emerged between mothers and fathers ($F_{1,21}$ = 1.4029, p = .2495; mothers' OT mean = 592.94 pM, SD = 219; fathers OT mean = 1042.47 pM, SD = 836.09). Similarly, no mother–father differences were found in AVP levels ($F_{1,21}$ = 0.7605, p = .3935, mothers' AVP mean = 207.1 pM, SD = 60.87; fathers' AVP mean = 263.38 pM, SD = 218.831).

Whole-Brain Hormone Correlations

When considering the brain activations in the contrast own infant>standard infant with OT or AVP as a covariate, differences were found between mothers and fathers.

Oxytocin. Figure 3 and Table 3 present correlations between brain areas that responded to the contrast own infant>standard infant and OT levels separately for mothers and fathers (random effect, uncorrected, p = .0071, cluster size

FIGURE 2 Differences between mothers' and fathers' brain responses to own-infant video. Note: Analysis of covariance (ANCOVA) of blood oxygen level–dependent (BOLD) functional magnetic resonance imaging (fMRI) statistical map of the "between subjects" factor contrasts between 15 mothers (in pink) and 15 fathers (in blue) and the "within-subject" factor contrasts between "own-infant" and "standard-infant" videos. Mothers showed greater positive activations of right amygdala and temporal, occipital, and parietal gyri compared with fathers. Fathers showed greater positive activations of the dorsal-pre-frontal cortex (dPFC) compared with mothers. IFG = inferior frontal gyrus; Y = −3, X = −20.



>3; Figures 3A to 3B and Table 3). Mothers' OT positively correlated with the GLM β values in the left insula, left IPL, left and right temporal cortices, left ventral ACC, and left NAcc. Fathers' OT negatively correlated with the left inferior and superior frontal gurus, left primary motor cortex, medial PFC, and left ACC.

Vasopressin. Figure 4 and Table 4 present correlations between brain areas that responded to the contrast own infant>standard infant and plasma AVP levels. Mothers' brain responses to own infant were negatively correlated with AVP in the bilateral superior-frontal gyrus, right precentral gyrus, right-medial-frontal gyrus, and right middle-temporal gyrus. In fathers, AVP correlated negatively with GLM β values in the right inferior-parietal lobule, right temporal pole, right IFG, right-medial-frontal gyrus, and left insula (random effect, uncorrected, p = .0071, cluster size > 3) (Figure 4, Table 4).

ROI Analysis of Right Amygdala

We extracted the signal from the right amygdala region and used it as a seed region for hormonal correlation.

Hormonal Correlation With Right Amygdala. Figure 5 present the correlations between the right amygdala ROI GLM β values in the contrast own-infant>standard-infant and plasma OT and AVP. We extracted the signal from the right amygdala that yielded the analysis of covariance between mothers' and fathers' brain activations in the contrast own-infant>standard-infant (Table 2), and correlated this signal with plasma OT and AVP in mothers and fathers separately. In mothers, the right-amygdala was positively correlated with maternal OT levels (r = 0.653, p = .0154, Figure 5), but such a correlation was not found in fathers (r = 0.3045, p = 0.362134). However, in fathers only, there was a trend for positive right-amygdala correlation with plasma

TABLE 2 Brain Activations in Mothers vs. Fathers in the Contrast Own-Infant vs. Standard-Infant Stimuli

	Peak X	Peak Y	Peak Z	BA	t	*p*	K
Mothers>Fathers							
Right superior temporal gyrus	42	11	−8	13	4.791	.000	168
Right post-central gyrus	18	−34	64	3	4.186	.000	411
Right fusiform gyrus	39	−1	−20	20	4.119	.000	226
Right middle temporal gyrus	42	−70	13	39	4.111	.000	1023
Right amygdala	12	−7	−17	34	4.019	.000	386
Right lentiform nucleus	15	8	−11		4.011	.000	128
Right cuneus	15	−85	19	18	3.687	.001	98
Right superior temporal gyrus	45	8	−23	38	3.552	.001	226
Right caudate	9	17	4		3.546	.001	126
Fathers>Mothers							
Left superior occipital gyrus	−36	−91	25	19	−4.182	.000	350
Left medial frontal gyrus	−21	32	28	9	−4.147	.000	239
Right superior temporal gyrus	48	−22	−8	22	−3.955	.000	105
Left medial frontal gyrus	−3	65	4	10	−3.878	.001	123
Left precuneus	−30	−76	56	7	−3.839	.001	100
Right middle temporal gyrus	63	−37	4	22	−3.802	.001	126
Left inferior parietal gyrus	−46	−67	49	7	−3.726	.001	178
Left inferior parietal gyrus	−42	−52	58	40	−3.693	.001	99

Note: X, Y, Z represent Talairach coordinates. N = 30 subjects. Cluster size > 3. Confidence threshold min = 2.79. K-Number of voxels in significant cluster. BA = Brodmann area.

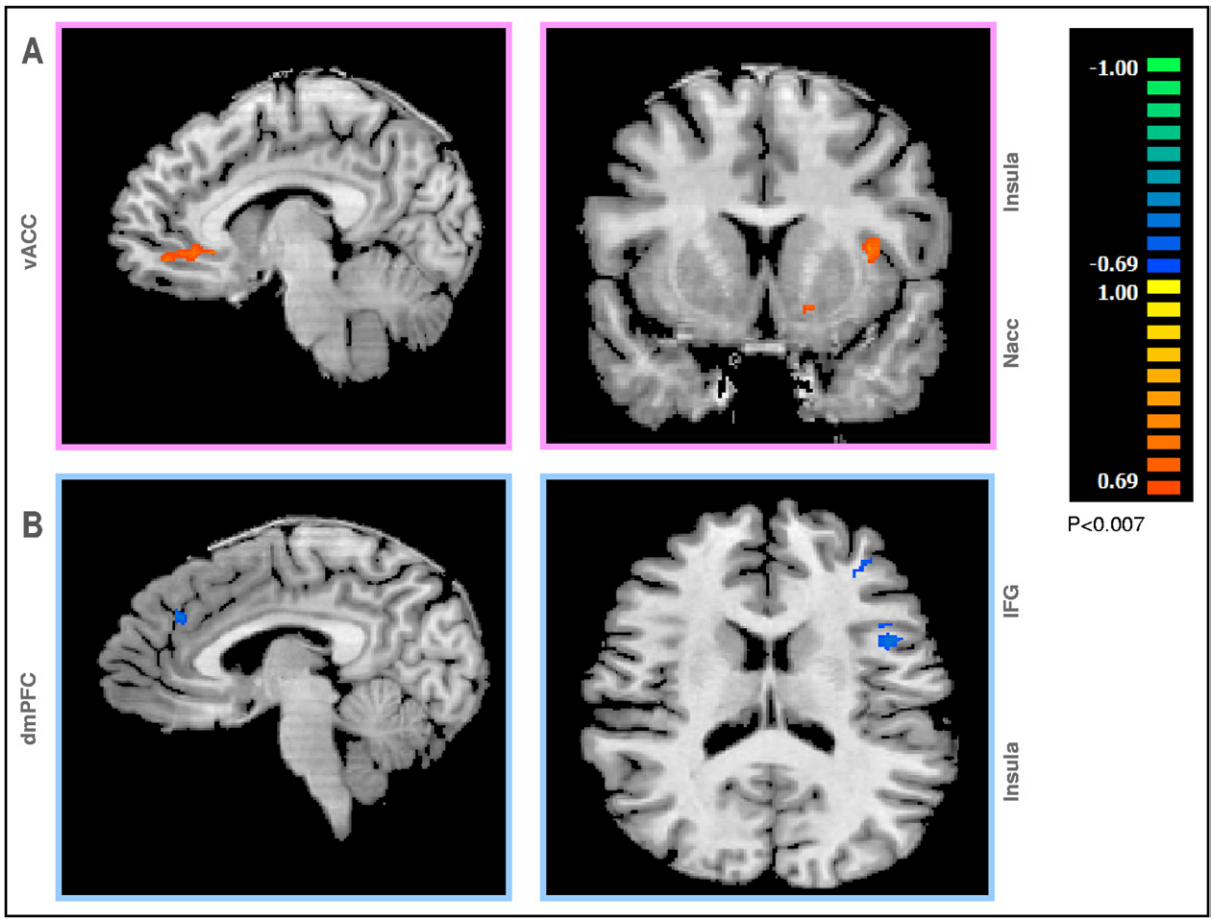
AVP (r = 0.686, p = .01972). However, because the correlation was influenced by a single subject, it was not possible to determine an AVP–amygdala correlation in fathers (Figure 5).

DISCUSSION

The current results suggest that mothers and fathers coordinate their brain responses to their own infant stimuli and point to the differential associations of mothers' and fathers' brain activations with neuropeptides supporting female and male bonding. Findings indicate that synchrony between mothers' and fathers' brain activations emerged in social–cortical networks associated with mentalizing and empathy,[8] including the insula, IPL, dmPFC, and IFG, suggesting that parents may share in real time their intuitive understanding of the infant's state and signals. Thus, the findings may point to potential links between mechanisms involved in pair bonding and those implicated in human parenting, and may suggest that co-parenting evolved on the basis of the higher mammals' capacity for online neural coordination with a social partner and the ability to represent the other's state in one's physiology.[31] However, because of our small sample size and the exploratory nature of our analysis, the current findings are preliminary and require much further research. If validated, such findings may have important implications for understanding the neurobiology of fatherhood and may extend evolutionary models on the emergence of co-parenting, the formation of social family units in humans, and the development of the infant's social brain within the matrix of neurobehavioral synchrony.

In addition to synchrony, results may also point to specificity in the brain networks that support mothering and fathering and suggest that, overall, mothering is marked by greater limbic responsiveness. Mothers exhibited greater amygdala activations to own-infant cues, consistent with findings for other mammals. Second, plasma OT, a key neurohormone underlying bond formation, correlated with limbic activations only among mothers, including the NAcc, amygdala, and ventral ACC. Such enhanced limbic–motivational activity in mothers may point to the deeply rooted, phylogenetically ancient role of mothering, whereas fathers' enhanced social–cognitive activations may reflect the more culturally facultative role of fathering.[5,11] It is possible that, because of its critical importance for infant

FIGURE 3 Correlations of plasma oxytocin levels with whole-brain activations in mothers and fathers. Note: Among mothers, plasma oxytocin levels correlated positively with activations in the ventral anterior cingulate cortex (vACC), left nucleus accumbens (NAcc), inferior parietal lobule (IPL), and temporal and frontal gyri (A) (X = −6, Y = 5). Among fathers, plasma oxytocin levels correlated negatively with activations in the dorsal medial prefrontal cortex (dmPFC), insula, inferior frontal gyrus (IFG), parietal cortex, and cerebellum (B) (X = 6, Z = 12).



survival, the evolution of mothering has been more tightly coupled with heightened responsiveness to infant cues and elevated amygdala response. It is important to note, however, that mothers also showed cortical responses and fathers showed limbic activations. The evolution of fathering and co-parenting requires much further research, and it is still unknown whether there are distinct patterns of "maternal" and "paternal" brain response or whether they reflect individual variability in emotional responsivity or caregiving opportunities.

As seen, the insula may play an important role in mother–father synchrony in response to their infant. The insula showed synchronized activity in the inter-couple correlation analysis (right middle insula), as well as correlations with OT in both mothers and fathers (left insula). These findings are consistent with research showing middle insula activations when subjects viewed their romantic partners compared with friends.[32] Along with the insula, in the IPL, IFG, and motor areas, there was evidence for mother–father brain synchrony. These regions constitute a social network involved in mentalization, action representation, simulation, mirroring, and attention functions.[9,33] These networks provide the basis for social interactions among kin and non-kin members of society,[8] and correlate with the minute-by-minute interactive synchrony between mother and infant.[4] Such social brain responsivity included higher-order cognitive functions implicated in mentalization and em-

TABLE 3 Oxytocin Correlations to Brain Areas in the Contrast Own-Infant vs. Standard-Infant Stimuli

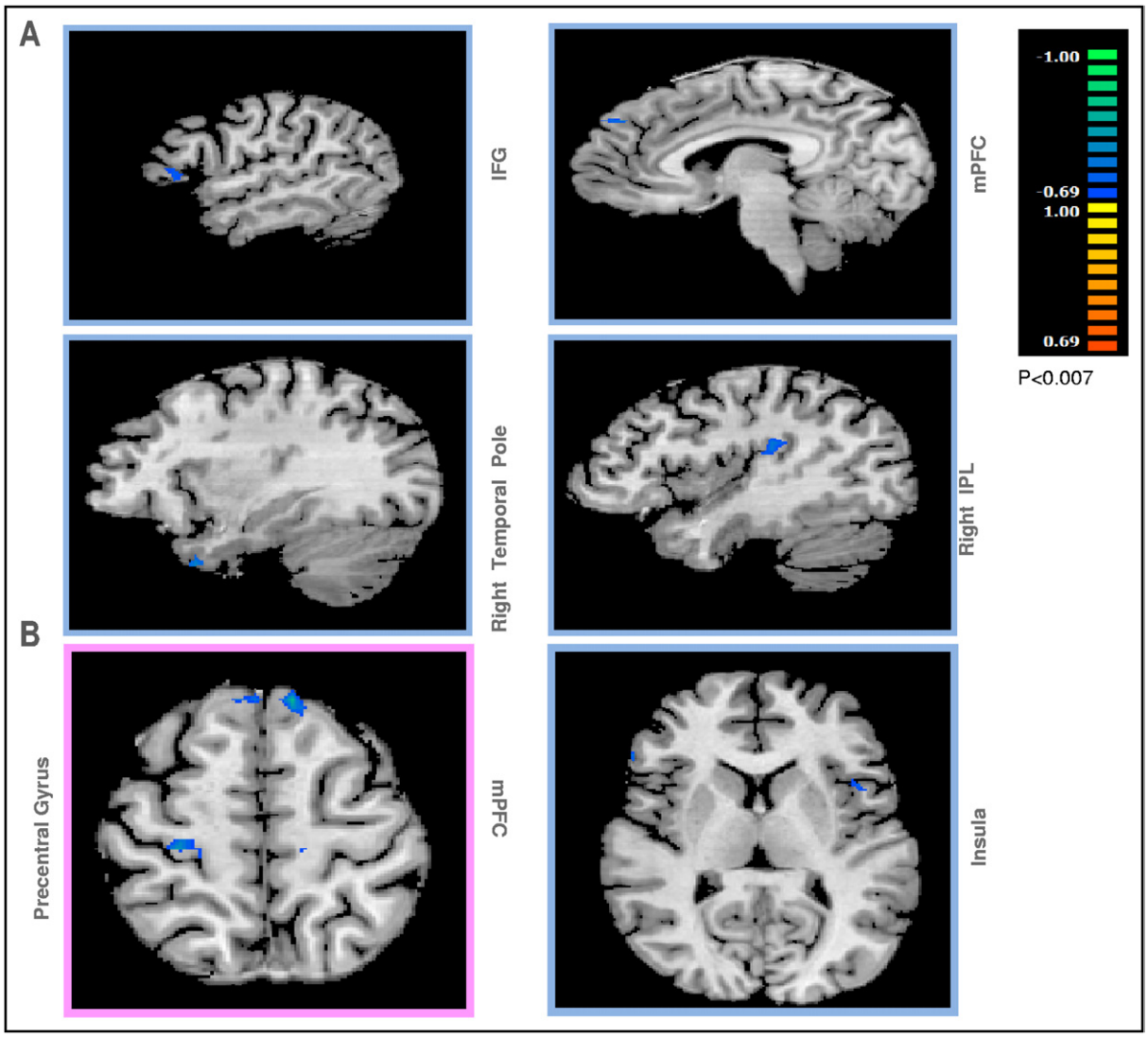
	Peak X	Peak Y	Peak Z	BA	r	*p*	K
Mothers							
Left insula	−33	2	13	13	0.868	.000	248
Left inferior parietal lobule	−45	−55	55	40	0.865	.000	91
Right middle temporal gyrus	54	−43	−14	20	0.861	.000	447
Left inferior parietal lobule	−45	−55	40	40	0.855	.000	129
Left superior temporal gyrus	−66	−43	7	22	0.851	.000	207
Left middle temporal gyrus	−54	−31	−2	21	0.832	.000	145
Left anterior cingulate gyrus	−9	35	−2	32	0.821	.001	474
Left superior frontal gyrus	0	59	28	9	0.820	.001	113
Right anterior cingulate gyrus	6	41	−2	32	0.801	.001	112
Left NAcc	−16	7	−6		0.800	.001	474
Left inferior parietal lobule	−55	−55	49	40	0.799	.001	83
Fathers							
Left inferior frontal gyrus	−45	8	13	13	−0.933	.000	1105
Left superior frontal gyrus	−18	41	31	9	−0.930	.000	1228
Left pre-central gyrus	−51	−4	40	6	−0.928	.000	563
Left medial frontal gyrus	−3	38	40	8	−0.923	.000	126
Right cerebellum	21	−73	−23		−0.903	.000	497
Left inferior parietal lobule	−48	−28	28	40	−0.902	.000	276
Right medial frontal gyrus	3	35	31	9	−0.866	.001	188
Left cingulate gyrus	0	17	40	32	−0.847	.001	163
Left medial frontal gyrus	−3	59	19	10	−0.823	.002	104

Note: Brain regions of mothers and fathers showing significant correlations with plasma oxytocin levels in the contrast own-infant>standard-infant. X, Y, Z represent Talairach coordinates. Fathers$_{(N)}$ = 11, cluster size > 3, p < .0071, min correlation threshold = 0.75. Mothers$_{(N)}$ = 13, cluster size > 3, p < .0071, min correlation threshold = 0.69. K-number of voxels in significant cluster. BA = Brodmann area; NAcc = nucleus accumbens.

pathy, as well as more basic functions of perception (lingual gyrus) and action representation (motor areas). Possibly, when perception–action regions are co-activated with mentalization regions, they have a social-attentive function that enhances the salience of the social context and the planning of adequate action. These uniform and synchronized parental responses in socially relevant brain areas likely represent a gender-independent parental orientation, which may provide the foundation for alloparenting and the formation of attachment bonds throughout life; however, these hypotheses require much further study.

The brain–OT correlations may provide additional support to the notion that mothering is guided by greater motivational–emotional focus. While keeping in mind that the hormonal analyses used an extremely small sample size of 13 mothers and 11 fathers, the preliminary results suggest that plasma OT levels significantly correlated with limbic–emotional brain areas among mothers, including the left NAcc, right amygdala, anterior insula, temporal gyri, and ventral-ACC. Among fathers, OT correlated with higher activations in cognitive areas, including the dorso-lateral PFC, dorsal ACC, IPC, and pre-central gyrus. Interestingly, the limbic–OT correlations in mothers were positive, whereas the cortical–OT correlations in fathers were negative. The dorso-medial PFC plays a regulatory role in organizing behavioral response to emotional stimuli, and higher paternal OT may have somewhat decreased this modulatory response. Oxytocin is central for the formation of social bonds in general and parenting in particular, and is critical for maternal behavior[2]; human studies have pointed to its role in social competencies, including trust, "mind-reading," and empathy.[34] Despite comparability in baseline plasma levels, which is consistent with previous research,[2] oxytocin was differentially related to limbic and cortical activations in mothers and fathers. It is possible that oxytocin acts differently on the development of mothering and fathering, through motivation enhancement or cognitive modulation. Yet, the underlying mechanisms for gender specificity in human parenting in relation to oxytocin brain receptors remain unclear.

FIGURE 4 Correlations of plasma vasopressin levels with whole-brain activations in mothers and fathers. Note: Among fathers, plasma vasopressin levels correlated negatively with activations in the inferior frontal gyrus (IFG) (A) (X = 53), temporal pole (B) (X = 31), and inferior parietal lobule (IPL) (C) (X = 45) (A). Among mothers, plasma vasopressin levels correlated negatively with activations in superior and medial frontal gyri and middle temporal gyrus (B). mPFC = medial pre-frontal cortex.



AVP has been implicated in male bonding by supporting defensive behaviors in mammals[35] and in social cognition and face perception in humans.[36] The current findings, the first to examine plasma AVP in relation to human fathering, support the special role of AVP in male bonding by showing its correlations with brain activations only among fathers. AVP–brain correlations emerged in fathers in the IFG and insula, highlighting the link between paternal affect and social cognition. The IFG and insula process mirror functions that are crucial for human social bonding, specifically between parents and infants, and the father's social response to the infant may be related to circulating levels of plasma AVP. This AVP–brain association may represent elevated AVP-dependent vigilance, and support the father's ability to read the intention of others to defend and respond to the young. However, it should also be noted that in small sample sizes, there is a greater chance for type II errors, and it is not possible to ascertain whether OT–limbic correlations are unique to mothers and AVP–brain

TABLE 4 Vasopressin Correlations to Brain Areas in the Contrast Own Infant vs. Standard Infant Stimuli

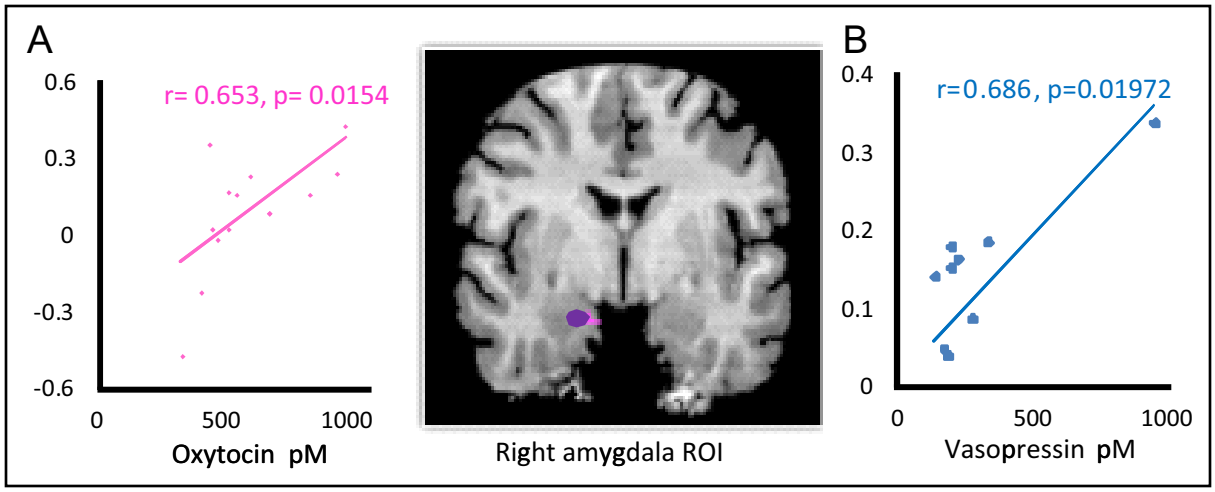
	Peak X	Peak Y	Peak Z	BA	r	*p*	K
Mothers							
Left superior frontal gyrus	−9	29	55	6	−0.929	.000	111
Right precentral gyrus	27	−28	52	4	−0.868	.000	250
Left medial frontal gyrus	−3	38	37	6	−0.859	.000	83
Right middle temporal gyrus	63	−25	−14	21	−0.855	.000	120
Left medial frontal gyrus	−12	−28	58	6	−0.837	.000	730
Right superior frontal gyrus	3	29	55	6	−0.822	.001	81
Fathers							
Right inferior parietal lobule	39	−28	22	40	−0.927	.000	279
Left middle frontal gyrus	−33	38	16	10	−0.894	.000	52
Right superior temporal gyrus	33	14	−36	38	−0.888	.000	142
Right inferior frontal gyrus	48	23	7	45	−0.858	.001	122
Right medial superior frontal gyrus	9	50	37	8	−0.855	.001	81
Left insula	−39	11	10	13	−0.800	.003	87

Note: Brain regions of mothers and fathers showing significant correlations to plasma vasopressin levels in the contrast own-infant>standard-infant. X, Y, Z represent Talairach coordinates. Fathers$_{(N)}$ = 11, cluster size > 3, p < .0071, mean correlation threshold = 0.75. Mothers$_{(N)}$ = 13, cluster size > 3, p < .0071, mean correlation threshold = 0.70. K-Number of voxels in significant cluster. BA = Brodmann area.

correlations are unique to fathers. Larger samples are thus required to validate the associations between OT and AVP with gender-specific patterns of parental brain activations described here.

The findings that synchrony between mothers' and fathers' brain activations in areas implicated in social cognition and empathy may suggest that brain activity can synchronize in real time between attachment partners within an affiliation-related context. These findings are consistent with current notions of "embodiment,"[31] which suggest that when individuals are required to perceive and to understand social signals, the interpretation of these signals is based on changes in these individuals' own physiology. This line of research was taken to suggest that bio-behavioral

FIGURE 5 Region-of-interest (ROI) analysis. Note: (A) Amygdala–vasopressin correlation in fathers. The right amygdala response to own-infant versus standard-infant contrast correlated positively with plasma vasopressin levels only in fathers. (B) Amygdala–oxytocin correlation in mothers. The right amygdala responses to own-infant versus standard-infant contrast correlated positively with plasma oxytocin levels only in mothers.



dyadic mechanisms provide the basis for the human capacity to understand complex emotional expressions in others. Combined with the present findings and the bio-behavioral synchrony conceptual model,[31] it is possible that the formation of human attachment includes a finely tuned adaptation of the parent and infant's brains in areas implicated in embodied simulation.

Limitations of the study include the relatively small sample size and homogeneous SES, the less restricted statistical thresholds, and the inability to measure OT and AVP in the brain. It is a preliminary study that used an exploratory approach at a whole-brain level with relatively liberal thresholds for statistical significance complemented with a priori regions of interests. In addition, we did not include non-infant stimuli in our paradigm. In the mother–father correlation analysis, we did not track the timely changes in synchronization or events that might influence the intercouple correlation; rather, the analysis correlated the activations across the signal time-course during the film and yielded a single r value for each maternal and paternal voxel.

Our findings are among the first to address the brain basis of fatherhood, and may suggest that human attachment involves the online coordination between the neurobiological processes of two individuals within an attachment relationship. Although the findings are preliminary and require further validation, they may shed light on process of brain-to-brain synchrony in the formation of human attachment, and contribute to the study of coparenting and the ways in which family units are constructed from the joint efforts of parents raising their infants. As fathers' role in childcare is increasing, the neurobiology of fatherhood is among the key question for future research. Finally, future research on conditions associated with disruptions to social functioning or parent–infant bonding is required in order to construct more specific interventions based on the coordination of brain mechanisms and behavioral expression.

Clinical Guidance

- Research has demonstrated that attachment bonds are formed through processes of *bio-behavioral synchrony*—the coordination of physiology and behavior between attachment partners. Here we examined whether mothers and fathers synchronize their brain response to their own infant's cues.
- Mothers and fathers synchronized brain activations online to own-infant video in brain areas implicated in social cognition, theory of mind, and empathy. Such brain synchrony may help parents to jointly read their infant's nonverbal communications and to plan adequate parenting.
- Mothers showed greater activations in limbic areas, and fathers showed greater activations in social–cognitive cortical areas. These were differentially correlated with oxytocin and vasopressin, neuropeptides associated with female and male bonding.
- These findings are the first to demonstrate brain synchrony between attachment partners in empathy-related networks. Conditions associated with early social dysfunctions, such as autism, are linked with less optimal functioning of these networks, and the findings may suggest disruptions in the capacity for brain-to-brain synchrony.

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