What's in a Smile? Maternal Brain Responses to Infant Facial Cues

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Abstract

Objectives—To determine how a mother's brain responds to her own baby's facial expressions, comparing happy, neutral and sad face affect.

Methods—In an event-related functional MRI study, 28 first-time mothers were shown novel face images of their own 5–10 month-old baby and a matched unknown baby. Sixty unique stimuli from 6 categories (own-happy, own-neutral, own-sad, unknown-happy, unknown-neutral and unknown-sad) were presented randomly for 2 seconds each, with a variable 2–6 second inter-stimulus interval.

Results—Key dopamine-associated reward processing regions of the brain were activated when mothers viewed their own baby's face, compared to an unknown baby face. These included the ventral tegmental area / substantia nigra regions, the striatum, and frontal lobe regions involved in 1) emotion processing (medial prefrontal, anterior cingulate and insula cortex), 2) cognition (dorsolateral prefrontal cortex) and 3) motor/behavioral outputs (primary motor area) ($P<0.001$, false discovery rate corrected [FDR] $q<0.05$). Happy, but not neutral or sad own-infant faces, activated nigrostriatal brain regions interconnected by dopaminergic neurons ($P<0.0005$, FDR $q<0.05$), including the substantia nigra and dorsal putamen. A region-of-interest analysis revealed that activation in these regions was related to positive infant affect (happy>neutral>sad) for each own-unknown baby face contrast.

Conclusions—When first-time mothers see their own baby's face, an extensive brain network appears to be activated, wherein affective and cognitive information may be integrated and directed toward motor/behavioral outputs. Dopaminergic reward-related brain regions are activated specifically in response to happy, but not sad, baby faces. Understanding how a mother responds uniquely to her own baby, when smiling or crying, may be the first step in understanding the neural basis of mother-infant attachment.

(4) cues. These stimuli, such as a hunger cry or smiling face, are powerful motivators for a mother to respond, either through caregiving, physical touch, speech or play. Animal research suggests that infant-responsive maternal behavior is causally related to the offspring's long-term developmental outcome in a number of domains, including cognitive development (5; 6) , stress reactivity (7–9) and maternal behavior in adulthood (7;10). Factors that restrict a mother's ability to respond to her baby's cues, such as depression (11), substance abuse (12) or even prolonged mother-infant separation (13) may result in adverse developmental outcomes for children (11;12;14;15). In addition, the ability to link these sensory cues with the underlying needs of an infant, and differentially respond to such needs, is thought to be the basis for establishing secure mother-infant attachment (15–17). Thus, a mother's behavioral and brain response to her infant's cues may be an important predictor of infant development.

Over recent years, several research groups have sought to better understand how a mother's brain responds to her child's auditory or visual cues, using functional MRI (fMRI) (18–23). One common theme emerging from these studies has been the possible role of the mesocorticolimbic dopamine system in processing reward-based signals and motivating maternal care, as seen in animal models (see review (24)). Several studies have shown that the striatum, a key projection of midbrain dopamine neurons which includes the putamen and caudate head, is activated in response to face images of a mother's own child compared to unknown (or familiar but unrelated) children (22;23), as well as to infant cry stimuli (18). Similar activation patterns have been seen in response to pictures of romantic partners (22), beautiful faces (25) and sexual stimuli (26), suggesting a link between brain reward circuits and attachment.

However, some maternal response studies have failed to show striatal activation (20;21), among other important differences. The amygdala, for example, is strongly activated in some studies (20;23), but deactivated in another (22). Since the amygdala plays an important role in processing face affect (27), and its response may be modulated by dopamine (28;29), differences in baby face affect may have been a confounding factor. Although most baby face studies sought to standardize face affect, none of them specifically controlled for variation in affect, or examined response differences related to facial affect. In addition, most prior studies have had a small sample size (10 or fewer subjects) or used a suboptimal fixed effects analysis (24) which prevents generalization of the results to the population from which the sample was drawn (30).

This study includes a relatively large sample of first-time mothers and their babies, specifically comparing maternal brain responses to baby face stimuli grouped into happy, neutral and sad affect. We predicted that "own baby" faces compared to "unknown" faces, would activate dopamine-associated reward-processing brain regions, including the ventral striatum and prefrontal cortex, and that the contrast in these regions would be greater for smiling baby faces than neutral or sad faces. Based on pilot results (31) and results from infant cry studies (18), we also predicted that sad faces from a mother's own baby compared to an unknown baby would activate the anterior cingulate cortex, which is involved in conflict monitoring (32), and both the insula and amygdala, regions often associated with negative emotion processing (27). Together these response patterns would help us to better define the neural basis of human mother-infant attachment.

METHODS

Subjects

This cohort is part of larger longitudinal study of mother-infant attachment, including 43 women who were enrolled during the third trimester of pregnancy. Subjects were recruited from prenatal clinics, local church groups, and poster, magazine and internet advertisements.

Each woman was screened for recruitment by phone or by completing an online questionnaire. Inclusion criteria included: first-time singleton pregnancy, right handedness, non-smoking during pregnancy, not currently on psychotropic medications, and no contraindications for MRI scanning (such as metal implants or severe claustrophobia). At the time of the fMRI scanning visit, approximately one year after enrollment, 5 women were lost to follow-up or declined further participation and 10 were unable to be scanned (9 due to a second pregnancy and one because of a past history of seizures), leaving 28 scanned women. During the second scanning run, data was only available for 26 women, because of unacceptable head motion in one case, and scanner failure in another.

The protocol was approved by the Institutional Review Board at Baylor College of Medicine, Houston, Texas, and all subjects provided written informed consent.

Experimental Design

Prenatal Session—During the third trimester of pregnancy, enrolled women provided sociodemographic information from which was calculated the Hollingshead SES score. They also participated in a variety of psychometric tests, including the Adult Attachment Interview, the Personality Disorder Questionnaire 4+ (PDQ4+), the McLean Screening Instrument for Borderline Personality Disorder (MSI-BPD) and the Beck Depression Inventory (BDI)(33).

Videotaping Session—At around 7 months post-delivery, each baby was videotaped in a standard setting at the Human Neuroimaging Laboratory, Baylor College of Medicine. Smiling faces were elicited by the experimenters interacting with the babies using a variety of age-appropriate toys, and crying faces were obtained by leaving the baby alone in the room (observed from behind a one-way mirror) with the video camera recording facial expressions. The mothers did not observe the videotaping, to ensure that each baby face image was novel when presented during the subsequent scanning session. At this visit, the mothers also updated their demographic information and completed another BDI.

Baby face still images encompassing various affect levels – happy, neutral and sad – were then captured from the videotape. Using a facial affect coding scheme, based on Cole et al (34), these images were classified by a trained research assistant into one of five affect groups: very happy, happy, neutral, sad or very sad. Excellent inter-observer reliability was demonstrated, based on 466 double coded images (Pearson correlation coefficient 0.925, 2-tailed, $P<0.001$). Control baby face images, unknown to each mother, were collected from the babies of other enrolled mothers or mothers involved in the pilot study. Each subject baby was matched to a single control baby, with an equal number of face images from each affect group. Wherever possible, the two babies were also matched on age and race. In cases of mixed race, the matching was based on a combination of race, complexion and hair color. Gender was matched if there were any obvious distinguishing features, such as earrings or longer hair. Each baby had been videotaped in a gender-neutral white jumpsuit. All images were standardized for size, orientation and background using Adobe Photoshop.

Scanning Session—A minimum of 3 months after the videotaping session, each mother attended a scanning session at the Human Neuroimaging Laboratory. Immediately prior to scanning, the mother participated in a one-hour long semi-structured interview, the Parent Development Interview (35), which prompted the mother to reflect on her relationship with her child. This provided a common setting for each mother prior to viewing the baby face images in the scanner.

The mother then participated in two functional MRI runs, each time passively viewing a series of 60 unique baby face images, 30 of her own baby and 30 of an unknown baby face. Each mother was informed that her “brain activity will be monitored using functional MRI while

she is shown pictures of her own baby and babies unknown to her" (recruitment brochure). Using an event-related fMRI design, randomly presented images were viewed for 2 seconds, with a random inter-stimulus interval of 2, 4 or 6 seconds (Figure 1). The 60 images were equally divided into 3 affect groups – happy, neutral or sad, with the intensity of happy and sad affect balanced between the "own" and "unknown" faces. The order of the images from each of the 6 groups (OH, ON, OS, UH, UN, US) was pseudo-randomized within and between each run, but not between subjects. There were no significant differences in the timing of "own" and "unknown" baby face images (natural log of mean presentation times, paired samples t-test, t= 0.73, df=29, *P*=0.47), or in the OH>UH, ON>UN or OS>US comparisons (df=9; Happy: t=1.52, *P*=0.16; Neutral: t=0.72, *P*=0.49; Sad: t= 1.69, *P*=0.13).

All imaging was performed using a 3 Tesla Siemens Allegra head-only MRI scanner. Visual images were generated using a computer controlled LCD projector, and presented to the mother via an overhead mirror display. High-resolution T1-weighted structural images (192 slices, in plane resolution 256 x 256; field of view [FOV] 245mm; slice thickness 1mm) were acquired first. Regional brain activation was assessed by measuring changes in blood-oxygen-level-dependent functional MRI signal (BOLD-fMRI). Subjects underwent two whole-brain functional runs of around 185 scans each (gradient recalled echo planar imaging; 37 slices; repetition time [TR] 2000 msec; echo time [TE] 25 msec; flip angle, 90 degrees; 64 x 64 matrix [in plane resolution]; FOV 220mm; slice thickness 3mm; gap thickness 1mm). Slices were positioned 30 degrees to the anterior commissure / posterior commissure (ACPC) line in the axial plane, downward from posterior to anterior, which (along with a reduced TE and slice thickness) has been shown to optimize visualization of the orbitofrontal cortex (36).

After the scanning session, each mother was asked to rate each of the baby face images on how they thought the baby was feeling, as well as their own feelings of pleasure or arousal, using

dimensional volume-time course data. For presentation purposes, the final activation map was interpolated into a 1 x 1 x 1 mm resolution.

For each functional run of the event-related data, a BrainVoyager protocol file was created, representing the timing of each stimulus event. The six baby face stimulus types in the design matrix included Own-Happy (OH), Own-Neutral (ON), Own-Sad (OS), Unknown-Happy (UH), Unknown-Neutral (UN) and Unknown-Sad (US) (Figure 1). Each predictor was then convolved with a double-gamma hemodynamic response function (43). Using the General Linear Model (GLM), group effects were evaluated using a random effects analysis, with a % time course transformation applied to each run of each subject separately. In the random effects analysis, statistical maps were created for each individual subject before being subjected to a second level of statistical analysis, allowing generalization to the sample population of first-time mothers. Main effects and possible interaction effects of infant "identity" and "affect" (Figure 1) were explored using 2-factor repeated measure ANOVAs (F-test, df=2,54). Group t-maps (2-tailed, df=27) were also generated after specifying a particular contrast in stimulus types (e.g. OH>UH), and were visualized on an averaged 3D anatomical image, which was created from all of the individual subject images.

The false discovery rate (FDR) approach (44) was used to correct for multiple comparisons at a threshold of $q<0.05$, which accepts 5% of the discovered (supra-threshold) voxels as false positives. A cluster threshold of 100 mm^3 (or approximately 4 voxels) was used, except in the brainstem, where a threshold of 30 mm^3 (or around 1 voxel) was used to reveal activation of smaller nuclei. Anatomical regions were confirmed using the automated "Talairach Daemon" (searching for "nearest gray matter") (45), and manually, using a human brain atlas (46). Brodmann Areas (BA) were defined using the BrainVoyager Brain Tutor (47).

Hemodynamic responses to event types (% BOLD signal change) were averaged and standardized across subjects, and plotted against time to create an event-related averaging plot for anatomical regions-of-interest. A random effects GLM analysis was performed on each volume individually.

RESULTS

Description of Subjects

The 28 mothers who participated in this study had a mean age of 29 years, were racially diverse (representative of the Houston population (48)), and middle to upper class (based on the Hollingshead Four-Factor Index of Social Status (49)), with 75% having completed higher education. Only one mother scored outside the normal range on WTAR-predicted WAIS-III IQ scores (range 81–120, median and mode=112) (Table 1). One other mother was classified as having "mild" depression symptoms based on the Beck Depression Inventory during the videotaping session, but none of the mothers reported significant symptoms during subsequent visits. There were no self-reports of current or past alcohol or drug abuse problems, or involvement in substance abuse treatment programs. However, 61% of mothers screened positive for one or more personality disorders on the PDQ4+, including 8 mothers for obsessive-compulsive and 8 for avoidant personality disorder (but none for borderline personality on the MSI-BPD). Although 93% of mothers reported returning to work by the time of the scanning session, 54% were still breastfeeding, and 43% reported that they were not separated from their child for more than 20 hours per week. Except for one baby born at 36 weeks gestation, the babies were full-term. At 14 months of age, only one child scored in the "at risk" range in one of five subscales of the Bayley Scales for Infant and Toddler Development, and this score was at the upper limit of the range. For this child, 3 out of the other 4 developmental scores were in the "competent" range. All other children were in the

"competent" or "emerging" range for each developmental subscale, including cognition, expressive and receptive communication, fine motor, and gross motor development (Table 1).

Maternal Brain Responses

Before addressing the specific hypotheses of this study, we examined maternal brain responses to affect-neutral baby faces compared to the no-face baseline. As expected, face stimuli activated brain regions along the ventral visual pathway from the primary visual cortex to the temporal lobe, including the fusiform gyrus and the so-called "fusiform face area" (Figure 2A&B) (50). However, after contrasting "own" and "unknown" baby faces (ON>UN), no significant activation remained, even at lowered statistical thresholds (Figure 2C). Thus, there was no significant difference in posterior visual pathway response between the own and unknown baby face stimuli.

Next, we tested our first hypothesis, regarding the main effect of infant "identity" (O>U) on maternal brain response. From the first scanning run, this revealed activation of forebrain regions involved in 1) emotion processing (medial prefrontal, anterior cingulate and insula cortex), 2) cognition (dorsolateral prefrontal cortex) and 3) motor/behavioral outputs (primary motor area, BA 4) ($F=13.6$ to16, df=1,27, $P<0.001$, FDR corrected $q<0.05$). Also activated were striatal and midbrain regions including the ventral striatum, head of caudate, putamen, ventral tegmental area (VTA) and substantia nigra. Other significant areas included regions of the inferior, middle and superior temporal gyri (including the fusiform gyrus and temporal pole), the lateral amygdala, thalamic nuclei and the hypothalamus (Table 2, Figure 3). No brain region was significantly activated by infant "affect" as a main effect ($F>15.66$, df=2,54, using a random effects model, FDR corrected $q<0.05$), nor was an "identity x affect" interaction effect seen, with or without FDR correction. No significant activation was seen for any contrast during the second scanning run, where the baby face stimuli from Run 1 were repeated and data from 2 subjects were missing.

As hypothesized, significant areas of activation were seen when the mothers were shown happy faces of their own baby compared to an unknown baby (OH>UH) ($P<0.0005$, FDR corrected $q<0.05$). Five specific regions of activation were seen in the limbic area (with a cluster threshold of 100 mm^3), and one in the midbrain (cluster threshold 30 mm^3), including bilateral putamen, left substantia nigra region, right thalamus, and the left lateral superior amygdala (Table 3). These regions essentially overlapped regions of significance in the main effects "identity" analysis for O>U (Figure 3).

A region-of-interest random effects analysis was then performed in each of the six OH>UH regions separately (all $P<0.0001$; Table 3). To explore how these results varied with infant affect, and ensure that they were not due to baby face familiarity differences alone, the analyses were repeated for neutral and sad affect faces. Significant activation was seen in four of the six regions using the "Own-Neutral" vs. "Unknown-Neutral" (ON>UN) contrast, although, as predicted, at much lower levels of statistical significance ($P<0.01$). No region showed significant activation when contrasting own vs. unknown sad faces. In all six regions, there appeared to be a progressive decrease in the % signal change differences, across happy, neutral and sad affect (Figure 4). The response to sad affect was significantly less than for happy affect in each region (paired sample t-tests, 2-tailed, df=27, $P<0.005$, except amygdala: $P<0.05$). A significant difference was also seen between happy and neutral affect in one region, and between neutral and sad affect in another (both $P<0.05$).

When the BOLD signal change was examined over time in each of these regions, the change from baseline fMRI response coincided precisely with the presentation onset of the baby face stimuli, and significant differences between the OH and UH stimuli responses were seen. As an example, in Figure 5 the left dorsal putamen and substantia nigra area, two key

interconnecting dopaminergic brain regions, showed a significant fMRI-BOLD response to own-happy faces but much less to neutral faces, and no response difference was seen in the sad face contrast.

Thus, although no significant "affect x identity" interaction effect was seen, these findings suggest that infant affect has a moderating effect in each of these 6 dopamine-associated brain regions, and that familiarity did not fully explain the results of the OH>UH contrast analysis.

Finally, we examined differences in maternal brain response to sad-affect baby faces. Compared to the no-face baseline, both "own" and "unknown" sad faces produced widespread brain activation, including the specifically hypothesized regions, anterior cingulate, insula and amygdala (t-test, df=27, $P<0.001$, FDR corrected $q<0.01$). However, as with the ON>UN contrast, no significant regions of activation remained after contrasting OS with US (at $P<0.001$, cluster 30 mm^2, uncorrected).

Behavioral Rating of Baby Faces

On viewing the baby face images outside the scanner, the mothers' own feelings were highly correlated with how they imagined the baby to be feeling ($r=0.82$, $p<0.001$). Crying baby faces, regardless of identity, resulted in more negative affective responses from the mothers, but the mothers' emotional responses were more tightly correlated with their own baby's affect than for unknown baby faces (Own: r=0.87; Unknown: r=0.80). That is, the mothers were more sensitive to their own babies' emotional states, than to unknown baby faces (slope own = 0.84, slope unknown = 0.49, $P<0.05$, two sample t-test, 2-tailed). The mothers also rated their feelings as being more "aroused" or intense for their own baby, compared to unknown baby faces ($P<0.01$, two sample t-test, 2-tailed).

DISCUSSION

As almost any mother will attest, seeing one's own baby smile is a uniquely pleasurable and rewarding experience. But what's in a smile, when we consider a mother's brain response? And how is seeing one's own baby linked to motivated behavior? This study shows that when first-time mothers observe their own baby's face, all of the key dopamine-associated reward-processing regions of the brain are activated, including the midbrain VTA / substantia nigra regions, the striatum and the prefrontal cortex, as well as the primary motor area. Smiling, but not neutral or sad, faces specifically activate nigrostriatal brain regions interconnected by dopaminergic neurons (51), with a graded response dependent on infant affect (happy>neutral>sad).

Two other studies have also shown maternal brain activation in the VTA / substantia nigra and the striatum in response to child-related stimuli (Bartels and Zeki (22) for face stimuli of older children and Lorberbaum et al (18) for infant cry stimuli). In primates, Haber et al (51) demonstrated important anatomical feed-forward loops between the striatum and the VTA / substantia nigra region, suggesting that these striatonigrostriatal circuits funnel information between ventromedial (limbic), central (associative) and dorsolateral (motor) striatal regions (Figure 6). Each striatal region is integrally connected to a corresponding region of the midbrain's VTA and substantia nigra via ascending and descending dopaminergic neurons. Likewise, there are corresponding connections between the striatum and the forebrain, including those involved in emotion processing (medial prefrontal, anterior cingulate, insula), cognition (dorsolateral prefrontal) and motor/behavioral outputs (primary motor area) (51). Thus, the striatum is believed to be an important relay station between the limbic and motor systems, integrating affective information from limbic regions with cognitive information from the prefrontal cortex, in shaping motor/behavioral responses.

In responding to infant social cues, whether positive or negative, mothers need to integrate both affective and cognitive information about their baby, and evaluate competing demands, before choosing the most appropriate behavioral response (52;53). For example, a distressed baby usually evokes an empathic emotional response from a mother, as well as cognitive processes to determine, based on past experience and knowledge, possible causes and remedies for her baby's distress. Likewise, a smiling baby face usually leads to positive affective arousal in a mother, associations with other rewarding experiences and contingent behavioral responses, such as smiling, caressing or playing.

The difference in striatal and midbrain responses seen in this study between happy, neutral and sad affect (Table 3; Figures 4 and 5) is consistent with other studies which show preferential activation for more appetitive or rewarding stimuli (54), including faces rated as more beautiful (25) or monetary reward (55). Non-human primate studies have shown that the firing rate of dopaminergic neurons is increased in response to "positive prediction errors", meaning unexpected natural or conditioned rewards (56). Perhaps a mother's own baby's unexpected smile, for example, may activate dopamine circuits via a similar mechanism. In rat dams, extracellular dopamine release in the ventral striatum is associated with an increase in maternal behaviors, with the dopamine signal preceding the onset of the behavior (57). Although functional MRI only measures blood-oxygen level dependent changes in brain activity, together these studies suggest that positive sensory cues from infants, such as a smiling facial expression, may stimulate dopamine release in the striatum, and promote responsive maternal care.

In this population of mothers, own-happy baby faces tended to activate associative and motor regions of the striatum, rather than the more affect-related regions of the ventral striatum and the VTA (51) (Figure 6). However, these regions were activated when all affect groups were combined in the O>U contrast (Table 2). Given that the OH>UH contrast used only one-third the number of images used in the O>U contrast (20 vs. 60), this may simply reflect insufficient statistical power. In fact, when statistical thresholds were lowered in the OH>UH contrast, a similar activation pattern was seen (data not shown). However, further research will explore whether this pattern varies with maternal characteristics, such as adult attachment classification, where affective and cognitive brain responses have been hypothesized to be key distinguishing features (52).

The fact that the mothers did not have a stronger response to their own baby's crying face, compared to an unknown baby's, was also surprising. It appears that, at least in this sample of mothers, the brain responds equally to own and unknown baby faces in distress. This was evident from the contrast between sad faces and baseline, which revealed widespread activation in response to both own and unknown sad baby faces, though with a similar pattern for each. Thus, in the contrast between OS and US, no significant activation remained. However, it is possible that differences in timing of the two conditions could have biased the results, with earlier images expected to produce a stronger hemodynamic response. Although the timing difference between own-sad and unknown-sad images was not statistically significant ($t = -1.69$, $P = 0.13$), own-sad images were seen somewhat earlier than unknown-sad images. This would, however, have biased the results in favor of own-sad images, rather than unknown-sad. Another possible explanation is that individual mothers respond differently to their own baby's sad face, some feeling distress themselves, others inhibiting their own negative affect. Future work looking at adult attachment strategies may reveal important individual differences in maternal brain response to sad infant affect.

One limitation of this study is that the mothers were scanned at varying times post-partum (between 7 and 17 months), viewing baby faces ranging from 5 to 10 months in age (Table 1). Although there is no published fMRI data on the question, mothers may respond differently to

their infant at differing ages, which may have influenced our results. Also, some key maternal brain regions identified in animal studies, such as the medial preoptic area (10) and ventral bed nucleus of the stria terminalis, were not activated in this study. However, other fMRI studies have only demonstrated activation of these areas in mothers of younger babies, during the first few months of life (18,24), suggesting that these regions may be more important during the early postpartum period.

While individual variation seen within this population (such as breastfeeding duration, mother-infant separation, and psychopathology risk) is another limitation in interpreting study findings, it also presents an opportunity for further research into the significance of these individual differences. In addition to understanding how prior experience may influence maternal brain responses, the present paradigm might also enable investigators to explore how these response patterns relate to current maternal behavior. For example, the difference in response between own and unknown happy faces in these dopamine-associated regions may be an index of the reward value or salience of the infant's face to the mother, which may in turn relate to maternal sensitivity or child neglect. This may further our understanding of brain processes that mediate the effect of prior experience on current maternal behavior.

Individual differences in affective and cognitive brain responses are fascinating topics for ongoing and future research. In some mothers, for example, a crying baby may trigger an angry response, or even physical abuse (58), rather than empathic caregiving. Likewise, in cases of maternal depression (11) or substance abuse (12), a smiling face may repeatedly fail to illicit positive caregiving. Depressed individuals show a decreased emotional response to happy faces, decreased accuracy in recognizing facial expressions, and increased memory for negative faces (59). Cocaine, a common drug of abuse among child-bearing-age women, and which activates both mesocorticolimbic and nigrostriatal dopamine systems (60–62), appears to compete with natural infant-related reward signals (63). This may relate to relatively high rates of child neglect in cocaine exposed mothers (64).

Important questions which are currently being examined include: What are the effects of maternal depression or substance abuse on brain responses to infant cues? How do brain responses predict differences in maternal sensitivity or attachment? What effect may these response differences have on a child's subsequent development or attachment security?

How a mother responds to her infant's behavioral cues may have an important role in shaping future child development. This study takes us one step closer to understanding the underlying brain processes and pathways involved in this important dyadic relationship.

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Figure 1.
Baby face presentation paradigm in functional MRI experiment. Ethnically-matched still baby face images were presented for 2 seconds, followed by a variable 2–6 second period of a blank screen. The 6 stimulus types outlined were presented in random order.

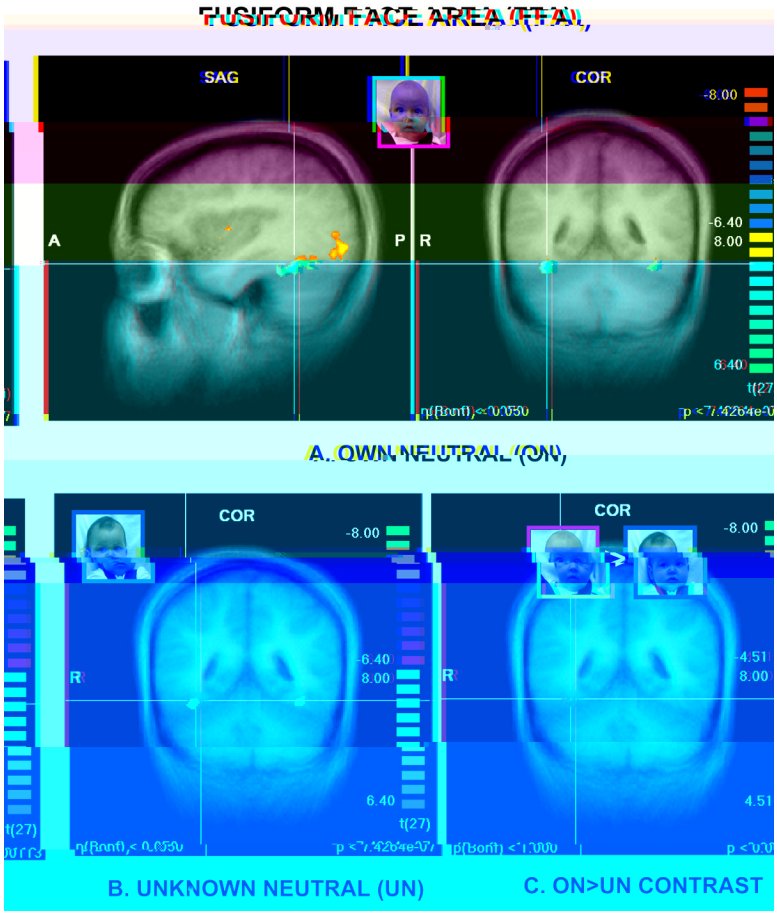

Figure 2.

Activation of ventral visual pathway, including the fusiform face area (Talairach coordinates 36, -46, -17) by own-neutral, as well as unknown-neutral baby faces A. Coronal and sagittal views of activation from own-neutral (ON) baby faces, compared to no-face baseline B. Coronal view of activation from unknown-neutral (UN) baby faces, compared to no-face baseline. C. Contrast between ON>UN, showing no remaining activation of visual pathway or fusiform face area. (A and B: $P<0.000001$, Bonferroni correction $P<0.05$, C: $P<0.0001$, uncorrected; cluster threshold 100 mm^3).

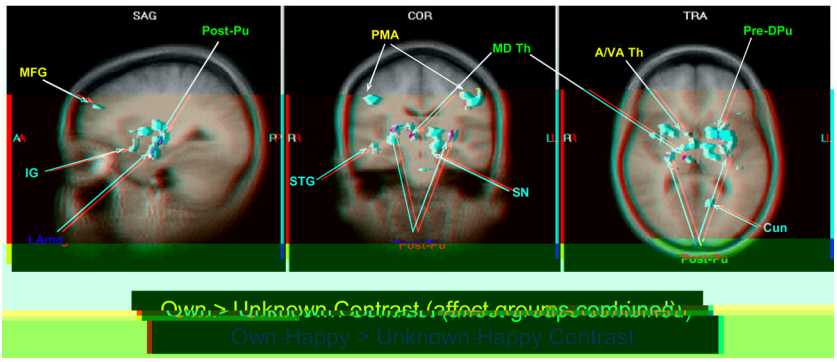

Figure 3.

Maternal brain activation in response to own infant vs. unknown infant happy faces (green regions and labels: t-test, df=27, $P<0.0001$, FDR corrected $q<0.05$, cluster threshold 100 mm^3) and all affect states combined (yellow regions and labels: F-test, df=1,27, $P<0.001$, FDR corrected $q<0.05$). Talairach coordinates -27, -16, 6. Abbreviation (left to right). Green labels: LAmg, lateral amygdala; Post-Pu, post-commissural putamen; MD Th, mediodorsal thalamus; Pre-DPu, pre-commissural dorsal putamen. Yellow labels: MFG, middle frontal gyrus; IG, insula gyrus; STG, superior temporal gyrus; PMA, primary motor area; SN, substantia nigra; A/VA Th, anterior / ventroanterior thalamus; Cun, cuneus.

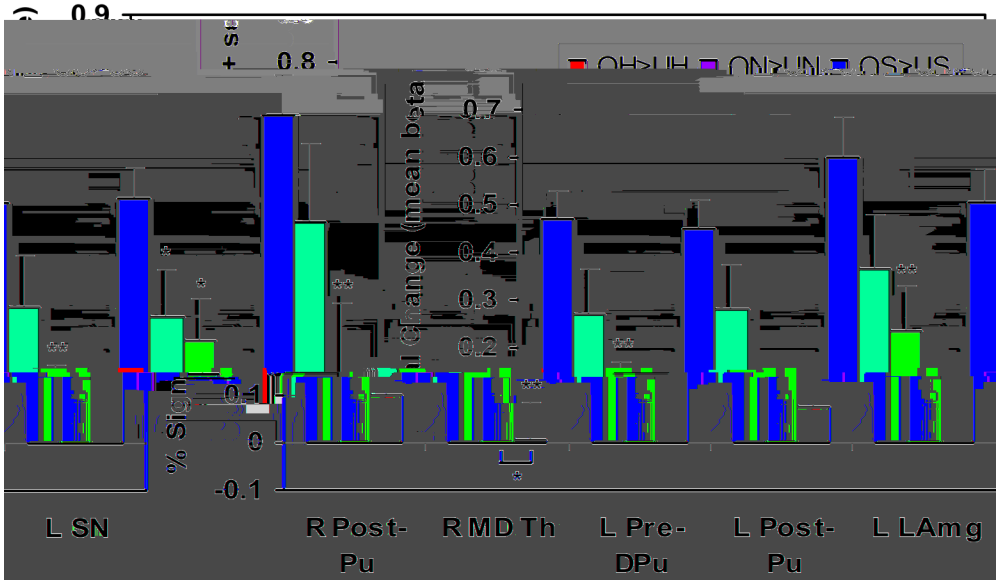

Figure 4.

Progressive decrease in activation depending on infant affect (happy>neutral>sad) in specified regions-of-interest. Paired sample t-tests (2-tailed, df=27) comparing happy affect with neutral or sad, except as noted. Abbreviations (left to right). R Post-Pu, right post-commissural putamen; R MD Th, right medial dorsal thalamus; L Pre-DPu, left pre-commissural dorsal putamen; L Post-Pu, left post-commissural putamen; L LAmg, left lateral amygdala; L SN, left substantia nigra. * $P<0.05$, ** $P<0.005$.

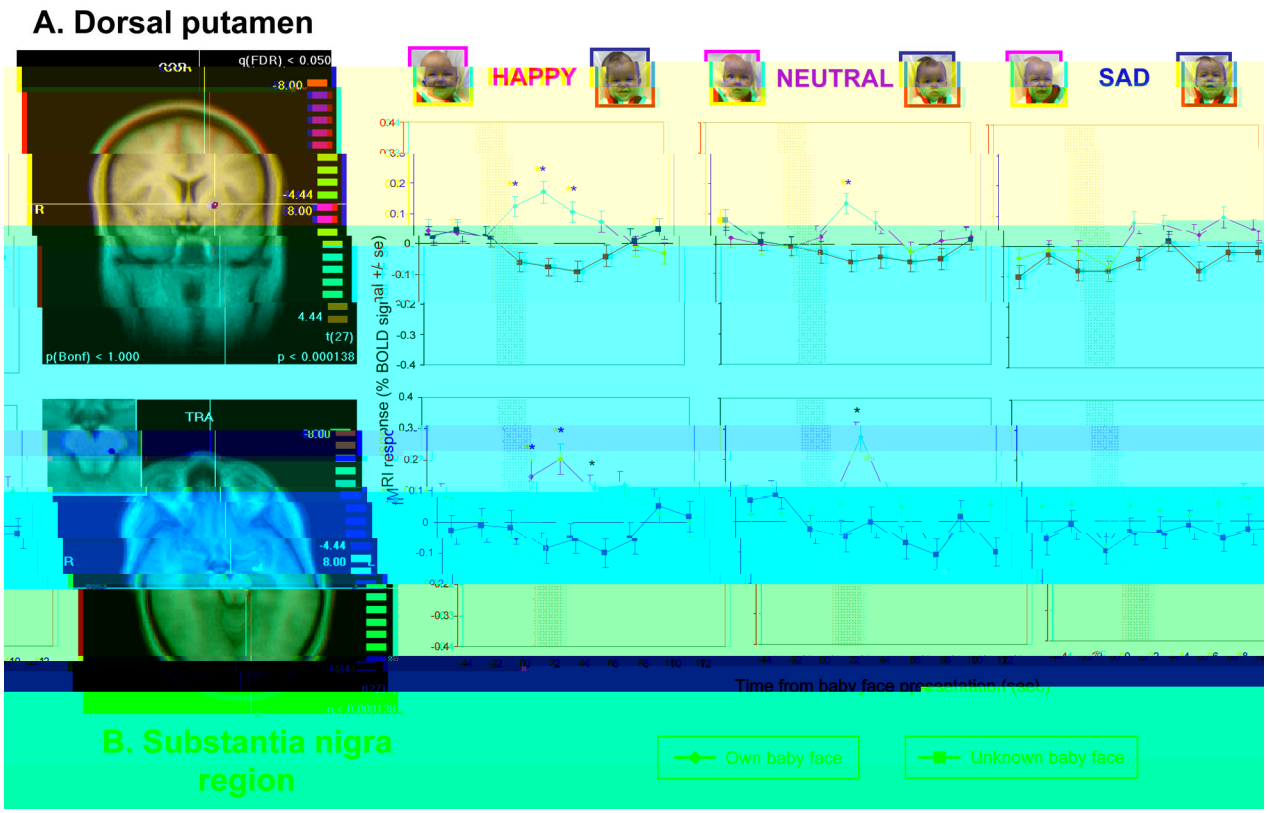

Figure 5.
Hemodynamic brain response of mothers viewing their own baby's face, compared to an unknown baby face in (A) the left dorsal putamen, and (B) the left substantia nigra (enlarged view inset) ($P<0.0001$, FDR corrected $q<0.05$). Event related averaging graphs for each region, separated by affect group.

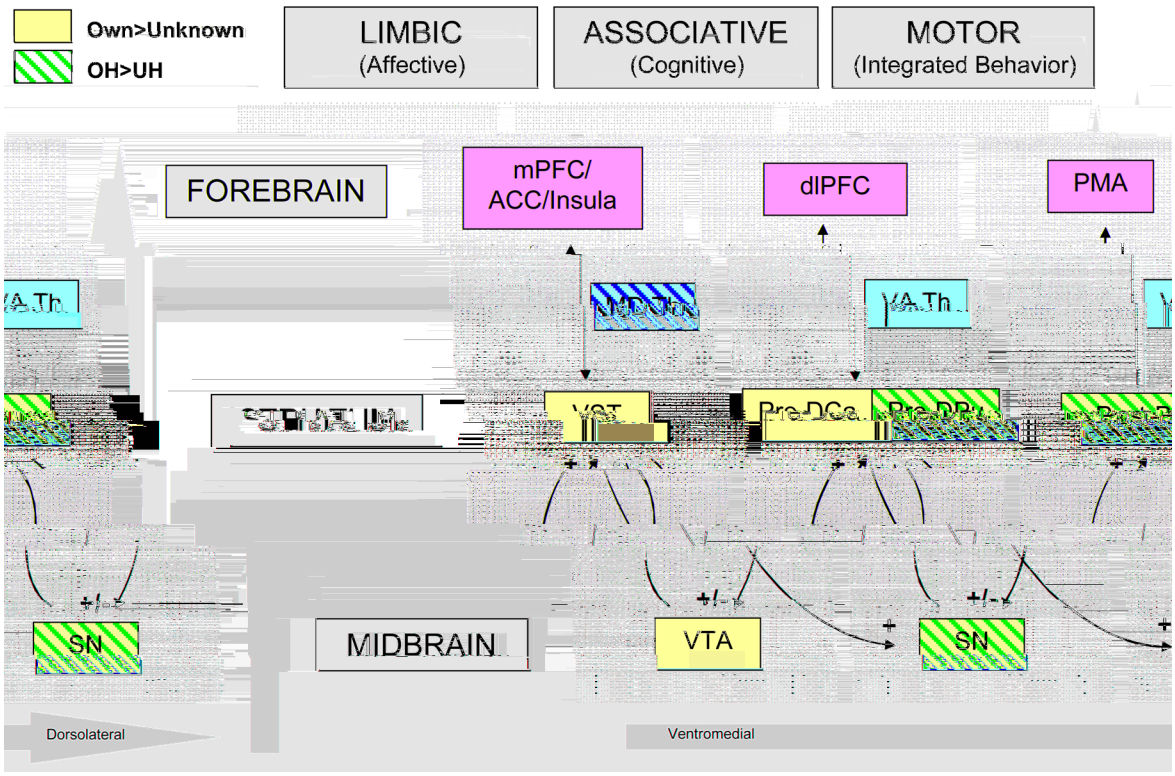

Figure 6.

Own vs. unknown baby faces activate prominent dopaminergic brain regions involved in cognitive, affective and motor information processing. Own-happy>Unknown-happy contrast (green shade boxes) and Own>Unknown contrast (all affect states combined; yellow boxes). Abbreviations (top to bottom). Green labels: MD Th, medial dorsal thalamus; Pre-DPu, pre-commissural dorsal putamen; Post-Pu, post-commissural putamen; SN, substantia nigra. Yellow labels: mPFC, medial prefrontal cortex; ACC, anterior cingulate cortex; dlPFC, dorsolateral prefrontal cortex; PMA, primary motor area; VA Th, ventral anterior thalamus; VST, ventral striatum; Pre-DCa, pre-commissural dorsal caudate; VTA, ventral tegmental area. OH, Own-happy baby faces; UH, Unknown-happy baby faces.

Table 1

Demographic information for study cohort (at time of scanning unless noted).

No.	Variables	Mean ± SD		Range
1	Age of mother, y	30.2 ± 5.0		20–42
2	Age of baby – videotaping session, mth	6.7 ± 1.6		5–10
3	Age of baby – scanning session, mth	10.7 ± 2.3		7–17
4	Hollingshead SES score (joint with partner)*	49.1 ± 12.7		24–66
5	Maternal IQ (WTAR-predicted WAIS-III)	108.7 ± 9.2		81–120
6	Maternal Race (n)			
	- White, non-Hispanic	13		
	- African American	7		
	- Hispanic	4		
	- Other	4		
7	Maternal Education (n)			
	- Post-graduate degree	13		
	- College/University degree	9		
	- Incomplete college	6		
8	Marital Status (n) *			
	- Married	20		
	- Single/never married	4		
	- Unmarried cohabitation	3		
9	Child Development at 14 months (n) *	**Competent**	**Emerging**	**At Risk**
	- Cognitive	21	5	1
	- Receptive Communication	25	2	0
	- Expressive Communication	21	6	0
	- Fine Motor	25	2	0
	- Gross Motor	27	0	0

* Data missing for one subject.

Table 2

Areas of significant activation from own vs. unknown baby face contrast (all affect groups combined, i.e. OH+ON+OS > UH+UN+US) (t-test, df=27, $P<0.001$, FDR corrected $q<0.05$; all cluster thresholds = 100 mm^3, except midbrain regions). All regions-of-interest $P<0.0001$. Talairach coordinates (x, y, z) represent center-of-gravity mean values for each region-of-interest. A large areas of activation involving the lentiform nuclei was divided manually according to anatomical regions.

Region-of-Interest / Cluster (Brodmann Area, BA)	Right Hemisphere		Left Hemisphere	
	x, y, z	Z-score O>U	x, y, z	Z-score O>U
Frontal Lobe				
Medial Prefrontal Cortex				
Superior frontal gyrus – medial (BA 6/9)	1, 2, 60	4.55	7, 39, 25	4.41
Superior frontal gyrus (BA 9/10)	3, 59, 29	4.97	-	-
Lateral Orbitofrontal Cortex				
Inferior frontal gyrus (BA 47)	-	-	43, 23, 1	5.09
Dorsolateral Prefrontal Cortex				
Inferior frontal gyrus (BA 44)	48, 8, 28	4.74	-	-
Middle frontal gyrus (BA 9)	-	-	24, 48, 32	4.17
Primary Motor Area / Somatosensory Cortex				
Pre- / Post-central gyrus (BA 4)	45, 17, 37	4.86	-	-
Parietal / Occipital Lobe				
Post-central gyrus (BA 3/40)	20, 27, 51	4.54	46, 17, 37	4.69
Lingual gyrus (BA 18/19)	-	-	15, 56, 2	4.48
Temporal Lobe (Lateral)				
Middle temporal gyrus (BA 21)	-	-	56, 38, 5	4.57
Middle temporal gyrus / temporal pole (BA 38)	48, 3, 13	5.36	47, 3, 12	4.97
Superior temporal gyrus (BA 22/21)	39, 41, 12	4.84	39, 28, 4	5.14
Inferior temporal / fusiform gyrus (BA 37)	38, 53, 7	4.30	41, 44, 17	5.09
Limbic Lobe / Sub-Lobar Regions				
Basal Ganglia				
Ventral striatum (pre-commissural)	-	-	13, 6, 4	4.88
Dorsal putamen (pre- commissural)	22, 5, 4	4.03	23, 2, 4	4.74
Putamen (post-commissural)	24, 17, 9	4.83	29, 12, 0	5.10
Putamen (post-commissural) – superior	-	-	26, 10, 10	4.80
Dorsal caudate (pre-commissural)	9, 5, 11	4.15	14, 2, 16	4.98
Thalamus / Hypothalamus				
Medial dorsal / centromedial thalamus	7, 20, 2	5.39	-	-
Ventral anterior / lateral thalamus	4, 7, 4	5.52	9, 9, 4	5.20
Ventral anterior / lateral thalamus	14, 10, 8	4.87	11, 16, 4	4.75
Hypothalamus	3, 8, 6	4.80	5, 8, 7	4.59
Medial Temporal Lobe				
Lateral superior amygdala	-	-	27, 6, 13	5.62
Parahippocampal gyrus (BA 36)	42, 37, 9	5.77	-	-
Insula Cortex				
Insula (inferior)	32, 3, 7	5.69	-	-
Insula	40, 3, 4	4.77	31, 5, 2	5.23
Insula (posterior) / planum polare	42, 19, 6	5.10	-	-
Cingulate Cortex				
Anterior cingulate cortex – pregenual (BA 24/32)	-	-	2, 37, 13	4.97
Anterior cingulate cortex – pregenual (BA 24)	-	-	3, 13, 32	4.62
Middle cingulate cortex (BA 24)	1, 2, 42	4.92	-	-
Posterior cingulate cortex – retrospenial (BA 31)	-	-	5, 53, 17	4.48
Posterior cingulate cortex – retrospenial / cuneus (BA 17)	-	-	8, 64, 10	4.75
Midbrain (Cluster threshold = 30 mm^3)				
Ventral tegmental area vicinity (midline)	1, 16, 15	5.56	-	-
Substantia nigra vicinity	-	-	8, 23, 9	4.93
Red nucleus vicinity	3, 21, 7	5.23	3, 21, 8	5.46

Region-of-Interest / Cluster (Brodmann Area, BA)	Right Hemisphere		Left Hemisphere	
	x, y, z	Z-score O>U	x, y, z	Z-score O>U
Cerebellum				
Cerebellum	38, 48, 25	4.78	34, 38, 28	4.97
Anterior cerebellum	-	-	2, 45, 39	4.69

Table 3

Areas of significant activation from own-happy vs. unknown-happy baby face contrast (t-test, df=27, $P<0.0001$, FDR corrected $q<0.05$). These regions-of-interest were then analyzed with respect to neutral and sad baby face contrasts. Talairach coordinates represent center-of-gravity mean values for each region-of-interest.

Region-of-Interest / Cluster		Z-score		
Anatomical Region	**Talairach coordinates (x, y, z)**	**OH>UH**	**ON>UN**	**OS>US**
Cerebrum (Cluster threshold = 100 mm^3)				
R putamen (post-commissural)	24, 17, 9	5.60***	2.70*	1.43
R medial dorsal / ventrolateral thalamic nucleus	9, 18, 4	5.60***	2.64*	0.09
L dorsal putamen (pre-commissural)	21, 2, 4	5.27***	2.88**	2.25
L putamen (post-commissural) / claustrum	27, 14, 1	5.35***	2.38	0.78
L lateral amygdala (superior)	30, 6, 12	5.56***	2.44	2.28
Midbrain (Cluster threshold = 30 mm^3)				
L substantia nigra (vicinity)	9, 22, 12	5.76***	2.65*	0.94

*$P<0.01$,

**$P<0.005$,

***$P<0.0001$.