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Human Maternal Brain Plasticity: Adaptation to Parenting

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Abstract

New mothers undergo dynamic neural changes that support positive adaptation to parenting and the development of mother-infant relationships. In this article, I review important psychological adaptations that mothers experience during pregnancy and the early postpartum period. I then review evidence of structural and functional plasticity in human mothers' brains, and explore how such plasticity supports mothers' psychological adaptation to parenting and sensitive maternal behaviors. Last, I discuss pregnancy and the early postpartum period as a window of vulnerabilities and opportunities when the human maternal brain is influenced by stress and psychopathology, but also receptive to interventions.

Keywords

brain imaging; neural plasticity; parenting; mothers; pregnancy

Pregnancy and the early postpartum period represent a sensitive period when new mothers adapt to the highly challenging tasks they encounter in taking care of a newborn. Whether mothers successfully adapt to parenting or not is critically associated with differences in quality of mother-infant relationships as well as infants' developmental outcomes. Animal research elegantly demonstrates dynamic adaptation in the maternal brain to support the transition to parenthood (Lonstein, Lévy, & Fleming, 2015). The goal of this chapter is to review empirical findings from recent neuroimaging studies showing that human mothers' brains also undergo dynamic structural and functional changes during pregnancy and the early postpartum period to facilitate their psychological and behavioral adaptation to parenting.

In this chapter, I first review psychological adaptation to parenting, focusing on two domains – enhanced sensitivity to infants and threats, and emotion regulation ability. Next, I review structural and functional plasticity of the human maternal brain to support such psychological adaptation. I then extend the review to include the associations among neural plasticity, parenting behaviors, and infant outcomes. Finally, I discuss implications of scientific progress, including identification of pregnancy and the early postpartum period as a sensitive period when the maternal brain is vulnerable to stress and psychopathology, but also receptive to interventions.

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Psychological Adaptation to Parenting

During pregnancy and the early postpartum period, there are normative psychological changes that support women's adaptation to parenthood. First, during late pregnancy, women show increased vigilance to threats (e.g. fearful and angry faces) which is considered to be adaptive for an enhanced ability to protect their expected infants from potential threats in the environment (Pearson, Lightman, & Evans, 2009). Second, during late pregnancy women exhibit greater sensitivity to infant cues (Pearson, Lightman, & Evans, 2011) and increased feelings of emotional attachment toward their fetus (Levine, Zagoory-Sharon, Feldman, & Weller, 2007). Such heightened maternal sensitivity to infants supports mothers' psychological adaptation to care for infants immediately when the baby is born and afterwards (Pearson et al., 2011).

Heightened sensitivity to infant cues among new mothers continues into the early postpartum period (Mascaro, Hackett, & Rilling, 2013; Mercer, 1985). New mothers typically exhibit heightened behavioral sensitivity toward infant cues such as cries, smells, and smiles (Thompson-Booth et al., 2014). This is demonstrated by the ability of an infant's gaze to elicit exaggerations in maternal vocalizations, facial expressions, and gazing during mother–infant interactions (Feldman, 2003; Papousek & Papousek, 2002). Moreover, during the early postpartum period, mothers exhibit increased levels of preoccupations, such as "checking and worrying" about their infants (Leckman et al., 2004). Parental preoccupation is considered to be a part of healthy maternal responses to infants that draw mothers close in order to meet the infant's physical and psychological needs (Bowlby, 1969; Winnicott, 1956). Typically, parental anxiety and preoccupation peaks immediately after childbirth and begins to diminish during the first 3 to 4 months postpartum (Feldman, Weller, Leckman, Kuint, & Eidelman, 1999; Kim, Mayes, Feldman, Leckman, & Swain, 2013; Leckman et al., 1999).

Functional Plasticity of the Maternal Brain

Pregnancy

In tandem with heightened psychological vigilance to threats, pregnant women exhibit heightened neural reactivity to threats. In a longitudinal study using near-infrared spectroscopy (NIRS), the functional plasticity of the prefrontal cortex (PFC) was examined in the context of attentional sensitivity to threatening information (i.e. fearful faces) in each of the three trimesters (Roos, Robertson, Lochner, Vythilingum, & Stein, 2011). Pregnant women exhibited greater PFC activation that was associated with increased attentional bias to threats, particularly during the second trimester. In another study using Event-Related Potentials (ERPs), pregnant women also exhibited neural activation patterns suggesting greater vigilance to threats (i.e. angry faces) in the third trimester (Raz, 2014). Thus, the findings provide evidence for neural functional plasticity during pregnancy, particularly toward late pregnancy, to support expectant mothers' heightened sensitivity to threats. Hyper-vigilance to threats is adaptive for better protection of infants from potential dangers. However, the studies point out that hyper-vigilance to threats among pregnant women may also increase their vulnerability to excessive levels of anxiety and, in turn, perinatal mood disorder diagnosis (Pearson, Lightman, & Evans, 2009; Raz, 2014; Roos et al., 2011).

Postpartum Period

Although NIRS and ERP are more commonly used during pregnancy in part to avoid fetal exposure to high magnetic fields, functional magnetic resonance imaging (fMRI) is most commonly used in research of the human maternal brain during the postpartum period. All studies included in this section have used fMRI. In tandem with psychological and behavioral sensitivity to infant cues, new mothers exhibit enhanced neural sensitivity to infant-related stimuli among several neural circuits that are important for parenting. First, new mothers exhibit increased activation in response to infant cues, particularly their own infant cues, in the reward/maternal motivation circuit (Atzil, Hendler, & Feldman, 2011; Strathearn, Li, Fonagy, & Montague, 2008). Animal studies have identified the neural circuit that is critically involved in reward and maternal motivation, which includes the midbrain (hypothalamus, ventral tegmental area, nucleus accumbens, and substantia nigra), striatum, and medial PFC (Numan, 2007). This circuit is activated by dopamine release and is involved in processing a range of rewards, such as food, drugs and sex. During the postpartum period, the increased levels of hormones such as oxytocin together with dopamine sensitize the circuit, particularly to infant-related information (Rutherford, Williams, Moy, Mayes, & Johns, 2011). Mothers show increased levels of activity in the reward circuit while looking at images of their babies' smile compared to looking at images of other babies (Barrett et al., 2012; Noriuchi, Kikuchi, & Senoo, 2008; Strathearn et al., 2008) as well as while listening to their babies' cry sounds compared to listening to other babies' cry sounds (Kim et al., 2011; Swain, Kim, & Ho, 2011).

Second, in response to infant cues, new mothers exhibit increased neural activation in the social information circuit which includes the insula, precuneus, superior temporal gyrus and fusiform gyrus (Hipwell, Guo, Phillips, Swain, & Moses-Kolko, 2015; Ho, Konrath, Brown, & Swain, 2014). Activation in this circuit has been associated with empathy (Decety, 2015) as well as self-monitoring and reflection (Lombardo et al., 2010; Schnell, Bluschke, Konradt, & Walter, 2011). Aberrant structure and functions have been associated with severe impairments in social competence such as autism (Uddin, Iacoboni, Lange, & Keenan, 2007). The increased activation in these regions may indicate their importance for mothers to accurately understand emotional and social cues from their own infant during interactions, and to appropriately responding to the cues.

Third, new mothers exhibit enhanced neural activation in the emotion regulation circuit including the anterior cingulate cortex, and the medial and lateral PFC (Barrett & Fleming, 2011; Kim et al., 2011; Rutherford, Wallace, Laurent, & Mayes, 2015). Increased anterior cingulate cortex and PFC activation are associated with regulation of negative emotional reactions (Ochsner, Silvers, & Buhle, 2012). The neural activation in these regions may play an important role in increasing effective emotion regulation, to cope with high levels of stress and demands of parenting, and to be able to sensitively respond to the infant's needs (Ho et al., 2014).

A recent meta-analysis of nine fMRI studies confirmed the role of these neural circuits in parenting (Rocchetti et al., 2014). The bilateral thalamus, striatum (putamen, globus pallidus, caudate), amygdala, substantia nigra, insula, inferior frontal gyrus, and temporal gyrus of new mothers all showed increased activation in response to their own baby compared to the control baby stimuli during the postpartum period (Rocchetti et al., 2014). Although longitudinal fMRI studies of human mothers are limited, preliminary data from one study (Swain et al., 2004) suggests that new mothers' neural activation patterns change over time to support enhanced psychological and behavioral sensitivity to infants. Compared to 2 to 4 weeks postpartum, at 12 to 16 weeks postpartum first-time mothers showed increased neural responses in the medial PFC and hypothalamus, key maternal motivation regions, in response to hearing their own baby cry (Swain et al., 2004). In regard to vigilance to threats during the postpartum period, a longitudinal study suggests neural functional plasticity over time to support psychological adaptation in mothers. Compared to non-postpartum controls, new mothers exhibited increased insula and inferior frontal gyrus activation in response to threats (i.e. angry and fearful faces) (Gingnell et al., 2015). However, from the first 2 days to 4–6 weeks postpartum, new mothers exhibited declines in neural reactivity to threats in these regions.

These findings together suggest that, during the early postpartum period, the maternal brain supports growing sensitivity, particularly to own infants, which further promotes the development of positive mother-infant relationships. On the other hand, the maternal brain may show gradual reductions in sensitivity to threats, and maternal anxiety and preoccupation levels subside over time (Feldman et al., 1999; Kim et al., 2013; Leckman et al., 1999). Sustained neural hyper-reactivity to threats may be a risk factor for anxiety and depression during the postpartum period (Gingnell et al., 2015).

Structural Plasticity of the Maternal Brain

Animal literature suggests that drastic changes in hormones, neurochemistry, and experience can lead to neural structural plasticity in the maternal brain during pregnancy and the early postpartum period (Brunton & Russell, 2008; Elyada & Mizrahi, 2015; Hillerer, Jacobs, Fischer, & Aigner, 2014; Lonstein, Lévy, & Fleming, 2015; Pawluski, Lambert, & Kinsley, 2016). However, little is known about structural changes in the human maternal brain. One existing study with human mothers using structural MRI longitudinally examined neural structural changes from pregnancy to the early postpartum period (Oatridge et al., 2002). In a sample of nine human mothers, the overall brain size and volume decreased throughout pregnancy. Brain size and volume was smallest at the time of the infant's birth, then brain size increased until it recovered back to the pre-pregnancy level by 6 months postpartum. Although it is still unclear why the brain size and volume decreased during pregnancy among human mothers, animal work suggests that hormonal changes for reproduction are associated with neural plasticity in the maternal brain during pregnancy (Leuner, Glasper, & Gould, 2010). Increased levels of estradiol and corticosterone have been associated with decreased volume and suppressed cell proliferation in the hippocampus during pregnancy (Galea et al., 2000; Pawluski, Brummelte, Barha, Crozier, & Galea, 2009).

Another study using structural MRI confirms the structural growth of the human maternal brain during the postpartum period, and further suggests that this growth may be particularly significant in brain regions important for parenting (Kim, Leckman, Mayes, Feldman, et al., 2010). When structural images of mothers' brains were compared between the first and third months postpartum, several large brain regions involved in maternal motivation and reward processing exhibited increases in gray matter volume, including the striatum, amygdala, hypothalamus, and the substantia nigra. Increases in gray matter volume were also observed in areas involved in sensory and social information processing, including the superior temporal gyrus, thalamus, insula, and pre- and post-central gyri. Finally, the inferior and medial frontal gyri as well as the anterior cingulate gyrus, regions that are associated with emotion regulation, also showed gray matter volume increase. Thus, the findings of Kim, Leckman, Mayes, Feldman, et al. (2010) suggest significant overlaps between functional and structural plasticity in the human maternal brain to support successful adaptation to parenting.

Relations of Maternal Neural Plasticity With Parenting Behaviors

Importantly, the structural and functional plasticity in the human maternal brain has been associated with individual differences in maternal thoughts and behaviors. In regards to structural plasticity, the greater the growth in the midbrain region, the higher the positive emotions a mother reported about her baby, which may indicate positive adaptation to parenthood in the third and fourth months postpartum (Kim, Leckman, Mayes, Feldman, et al., 2010).

Functional MRI studies also suggest that greater neural responses to a mother's own infant compared to unfamiliar infants support positive parenting behaviors of new mothers. At 4 to 6 months postpartum, neural activation patterns that are associated with sensitive and synchronous maternal behaviors (e.g. high coordination of gaze, touch, and vocalizations with infants) were examined (Atzil et al., 2011). In response to a mother's own baby video stimuli compared to control baby video stimuli, synchronous mothers showed greater activation in the nucleus accumbens, a key reward/motivation region, which was further functionally correlated with activity in the inferior frontal gyrus and medial frontal gyrus. Thus, reward-related neural responses to one's own infant were associated with enhanced neural connectivity for social information processing, which may further support synchronous mother-infant interactions. In another study, at 4 to 10 months postpartum, observation of positive mother-infant interactions was also associated with increased neural response to the mother's own infant videos (vs. control infant videos) in the putamen and inferior and middle frontal gyri, areas involved in maternal motivation and emotion regulation (Wan et al., 2014). Even at 18 months postpartum, observed maternal sensitivity during interactions with infants was associated with prefrontal activation (superior and inferior frontal gyrus), regions involved in emotion regulation, in response to a mother's own infant cry (versus a control infant cry) (Musser, Kaiser-Laurent, & Ablow, 2012).

The preceding studies above largely include new mothers who have a middle- to high-socioeconomic status. A recent study included 76 new mothers who had low socioeconomic status and ethnic/racial minority background (Hipwell et al., 2015). Such mothers are considered to be at higher risks for postpartum depression and difficulties in adjustment to parenthood because low socioeconomic status and ethnic/racial minority background are associated with greater levels of adversity in life (Kim & Bianco, 2014). In the study, increased neural sensitivity to one's own infant cry stimuli was associated with mothers' understanding of the infant's mental state, rather than observed maternal sensitivity, during interactions with infants at 4 months postpartum (Hipwell et al., 2015). Increased activation in the frontoinsular cortex and limbic regions, including the thalamus, amygdala, hippocampus, and putamen, were positively associated with mothers' verbal expressions about their understanding of their infants' intents or desires. The findings highlight the importance of mentalizing and understanding infants' emotional states and intents as they grow older and require more complex and sophisticated social interactions. This study provides evidence for the neural plasticity that supports these psychological processes in mothers (Hipwell et al., 2015).

Finally, maternal neural responses to infants during the early postpartum period can play a critical role for predicting positive infant socioemotional outcomes. Among 21 new mothers, high levels of mothers' anxious thoughts about their own infants and their parenting competencies at the first month postpartum predicted lower socioemotional competencies among their infants at 18–24 months of age (Kim et al., 2015). Among these mothers, high anxiety about parenting and infants was further associated with reduced activation in the substantia nigra, a key reward/motivation region, in response to their own infant cry compared to other infant cry sounds at the first month postpartum, suggesting reduced neural sensitivity to own infants (Kim et al., 2015).

The number of studies examining such associations in human mothers is still limited, and they vary widely in their methods, including the postpartum month at the time of the study and infant stimuli presented to the mothers. However, taken together, these findings suggest that during the early postpartum period, mothers' neural activation in regions important for maternal motivation, emotion regulation, and empathy in response to infant-related stimuli are significantly linked to caregiving behaviors for their infants.

Conclusion and Implications for At-Risk Mothers

It is important to note that the literature on neural plasticity in human mothers remains limited and evidence is often based on single studies. Until these findings are replicated, their interpretation requires caution. However, evidence available to date suggests that during pregnancy and the early postpartum period, mothers undergo psychological and biological adaptations to enhance sensitivity to infants and potential threats as well as emotion regulation ability. The human maternal brain exhibits great structural and functional plasticity that supports these adaptive processes. Furthermore, human mothers' neural activation in regions involved in increased maternal motivation and emotion regulation is particularly important for predicting sensitive parenting behaviors and strong emotional bonding with infants.

Such understanding also suggests that abnormality in neural plasticity may increase vulnerability for a difficult transition to parenting among some mothers. Indeed, during the prenatal and postnatal periods, mothers can be vulnerable to severe difficulties in mood regulation and stress. New mothers are exposed to a heightened level of risk for mood disorders such as postpartum depression and anxiety disorders (Kim & Bianco, 2014; Segre, O'Hara, Arndt, & Stuart, 2007). Sixty to 80% of new mothers report postpartum blues and up to 25% of all new mothers and fathers report postpartum depression, which has consistently been linked to adverse long-term impacts not only on their own well-being, but also the well-being of the infant (Goodman et al., 2011).

Dampened neural responses to infants have been observed among mothers who experience chronic stress, depression, substance abuse, and trauma. Mothers who were depressed exhibited reduced neural responses in emotion regulation and social information circuits in response to their own infant cry sounds compared to mothers who were not depressed (Laurent & Ablow, 2011). Mothers who used one or more substances (e.g. tobacco, alcohol) during pregnancy also show reduced responses in emotion regulation circuit in response to infant cry sounds (Landi et al., 2011). The reduced sensitivity to infant cry sounds in the brain may diminish a mother's ability to regulate her own emotions in response to the cry, which may lead to more frustration and lower motivation to care for infants. Mothers with posttraumatic stress disorders (PTSD) also exhibit reduced activation in the PFC, a part of emotion regulation circuit (Schechter et al., 2012). Last, mothers who report having received less warm and caring parenting from their own mothers in childhood exhibit reduced activations in the emotion regulation and social information circuits in response to infant cry sounds, compared to the mothers who reported having received more warm and caring parenting in childhood (Kim, Leckman, Mayes, Newman, et al., 2010).

In sum, pregnancy and the early postpartum period represent a sensitive period for the human maternal brain. Changes in the maternal brain are significant and are designed to support mothers in managing the new and demanding tasks of parenting and building strong relationships with their infants. However, different factors such as mood disorders, severe stress, and trauma may increase vulnerabilities in mothers by disrupting normative changes in the brain. Given high plasticity in the human maternal brain, the pregnancy and the early postpartum period may be a period during which the maternal brain can be highly responsive to both negative experience (e.g. stress) and positive experience (e.g. interventions). For example, after cognitive behavioral therapy during pregnancy, attentional sensitivity toward infant pictures was improved among depressed mothers, and became comparable to those of nondepressed pregnant women (Pearson et al., 2013_ENREF_43). Therefore, future prospective and longitudinal studies and intervention studies will be important to better map the temporal processes of neural changes in the human maternal brain throughout pregnancy and the early postpartum period, as well as to identify a time window for optimal maternal brain responses to interventions. These studies can inform intervention efforts to support positive maternal neural and behavioral transition to parenthood, as well as optimal infant development.

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