Review

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The adaptive human parental brain: implications for children's social development

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Although interest in the neurobiology of parent–infant bonding is a century old, neuroimaging of the human parental brain is recent. After summarizing current comparative research into the neurobiology of parenting, here I chart a global 'parental caregiving' network that integrates conserved structures supporting mammalian caregiving with later-evolving networks and implicates parenting in the evolution of higher order social functions aimed at maximizing infant survival. The response of the parental brain to bonding-related behavior and hormones, particularly oxytocin, and increased postpartum brain plasticity demonstrate adaptation to infant stimuli, childrearing experiences, and cultural contexts. Mechanisms of biobehavioral synchrony by which the parental brain shapes, and is shaped by, infant physiology and behavior emphasize the brain basis of caregiving for the cross-generation transmission of human sociality.

The brain basis of human parenting: an emerging field of inquiry

Parenting is the process most critically implicated in the survival and continuity of life on Earth. It is also the only social behavior observed across species and taxa, appearing in multiple forms from limited to extended, and provided to offspring variously by mothers only, mothers and fathers, father alone in some non-mammalian species, or collaboratively by parents and conspecifics. Thus, parenting likely contains both more evolutionarily conserved components than all other social phenomena on the one hand and the greatest plasticity on the other [1–3]. Moreover, parenting is the social phenomenon most profoundly affecting brain development of the young, necessitating flexibility and adaptation to diverse ecological conditions, and is reciprocally shaped by inputs from infant, partner, and colony [4–10]. Therefore, parenting provides a prototypical target for comparative research. Although interest in the neurobiology of parenting dates back to the early 20th century [11–13] and gained momentum once Lorenz had described social bonding in 1935 [14–17], the brain basis of human parental care is a recent area of inquiry, with most imaging studies appearing over the past 5 years, thus calling for an integrative perspective on the human parental brain.

Whereas several recent reviews ([1,18,19], but see also [20]) discussed the neurobiology of parenting from the animal research perspective, this review is human centered, focusing on the interface between conserved and human-specific components and addressing long-term effects of parental care on infant social development in light of human infants' protracted dependence and the extreme immaturity at birth of the human brain [21]. Three questions are addressed: (i) What is currently known about the brain networks that appear to support human parental care, their modulation by parenting-related hormones, and their sensitivity to multiple parenting determinants? (ii) What real-world implications do these hold for infant development? And (iii) can research

Glossary

Alloparental caregiving: caregiving to offspring by adults other than the biological parents, frequently observed across the animal kingdom and common in several human societies [110].
Biobehavioral synchrony: the online coordination of physiological and behavioral processes among affiliated members during social contact. Parent–infant biobehavioral synchrony is a mechanism that supports children's physiological and social growth and must be experienced during an early sensitive period (Box 2, main text). Disruptions to synchrony due to conditions such as maternal postpartum depression carry long-term effects on infant development [51].
Embodied simulation (mirror) network: includes the pre-SMA, IPL, and IFG. The 'mirror' network responds to both action performance and action observation, and enables one to simulate others' goals and actions in one's own brain [106].
Emotion regulation/executive network: marks the latest-evolving cortical structures, including the dlPFC, mOFC, MFG, and frontopolar cortex. It enables top-down control over attentional, emotional, and cognitive processes, and allows individuals to engage in multitasking, inhibit emotion, select actions, and hierarchically organize activity according to long-term goals [105].
Empathy network: includes the AI, dorsal anterior cingulate cortex, and SMA [101]. It supports the capacity to resonate with others' pain and emotions by forming shared circuits of first- and third-person experience [99,101], and to anchor feelings in the present moment [102].
Mentalizing network: includes the STS/STG, TPJ, precuneus, PCC, and vmPFC. It allows individuals to infer others' mental states by predicting relations between external events and internal states (i.e., theory of mind) [104].
Social brain: structures in the mirror, mentalizing, and empathy networks jointly define the human 'social brain'.

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on the parental brain shed further light on global topics in human sociality, including higher order social functions and the social brain? I hypothesize that the parental brain marks a peak expression of human evolution that integrates survival-related ancient functions with networks supporting the exquisite complexity and multifinality of the human brain, opening an important window into human-specific social functions such as the capacity to resonate with others' mental states (empathy) or to coordinate facial signals to enhance attachment (social synchrony).

The parental brain: animal models

Animal studies have mainly tested the parental brain in female rodents; therefore, less is known about fathers, nonhuman primates, or species forming an exclusive maternal–infant bond [6]. This research has described the critical role of the medial pre-optic area (MPOA) in the hypothalamus for initiation of maternal behavior. Primed by pregnancy hormones, particularly oxytocin and prolactin, the MPOA acts, via its projections to the mesolimbic dopamine circuits [especially the nucleus accumbens (NAcc) and ventral tegmental area (VTA)], to increase maternal reward from infant interaction, thus sensitizing a limbic network of maternal care [22–24]. In parallel, oxytocin acts directly on the VTA to facilitate dopamine release in NAcc [22], enhancing the mother's motivation to care for her young. The amygdala, similarly receiving projections from MPOA, increases maternal vigilance for infant signals [25,26], and oxytocin-primed synaptic plasticity of the amygdala-accessory olfactory bulb pathway supports formation of social memories by augmenting the salience of bonding-related cues [27].

The initiation of maternal behavior involves a two-stage process in female rodents that first suppresses their typical aversion to infant cues and then increases maternal motivation via MPOA–dopamine connections [6,25]. Studies in rodents describe the initiation and maintenance of maternal behavior as two distinct phases, the first hormone primed and automatic, the second more memory based and shaped by inputs from infant and nest [6,24]. Furthermore, parenting in rodents is accompanied by increased brain plasticity and research highlights the postpartum period as the time of highest plasticity in the adult brain [28]. Importantly, oxytocin functions as a modulator within this amygdala–hypothalamus–dopaminergic caregiving circuit and the increase in oxytocin during childbirth sensitizes this system in terms of activity, connectivity, and susceptibility to reorganization based on social experiences [29–31]. Findings in rodents [30] and primates [32] indicate that the oxytocin system of the infant's brain is organized through the mother's species-typical postpartum behavior and tactile contact. Yet, rodent studies have directed little attention to cortical processes, and have highlighted maternal care as being subcortical, hormonally controlled, and modulated by olfactory cues.

The human parental brain

Evolutionary conserved components

Several conserved aspects of parental care are observed in humans. Both the amygdala and reward circuitry are key components of the human parental brain and support parental vigilance and/or anxiety for infant safety as well as reward from the attachment relation [33]. Similarly, studies have pointed to increased brain plasticity in humans, which provides an opportunity for reorganization of the parent's brain [34]. Finally, the modulatory role of oxytocin in the subcortical network that supports mammalian caregiving also underpins multiple socio-affective functions in humans, including empathy, group cohesion, and social understanding [35]. Thus, the ancient system sensitized by pregnancy and triggered by the birth hormone is also implicated in a host of higher order sociocognitive functions throughout human life [36]. However, one important difference between the mammalian maternal care circuit and the human parental caregiving network is the connectivity of these subcortical structures to multiple insula-cingulate and frontotemporoparietal networks, which are integrated into the human parental care network along the subcortical areas described in rodents.

The exclusive human parental–infant bond

The exclusive human parental–infant bond represents a key departure from rodent models. Whereas rodent mothers promiscuously care for any infant in their surroundings, human bonding is person specific [37]. This exclusive bond requires representational and associative processes involving continuous network reorganization based on past experiences over a lengthy sensitive period, where specific pathways are built over time from reciprocal exchanges of parent and infant cues [38]. To some extent, such elaborate associative processes are human specific: it has been shown that the increase in size of associative cortex compared with sensory-motor areas represents the main departure of the human brain from that of chimpanzees, our closest relative [39]. Although exclusive bonding is also found in herding animals, such as sheep, bonding of lamb and ewe is mediated by olfactory cues [5]. With the evolution of large neocortex mammals, olfactory-centered bonding gave way to affiliative bonds based on multimodal signals, memory, and associative processes [40]. The exclusive human parent–infant bond involves brain plasticity required for the fine-tuning of the parent brain to inputs from each child via a process termed 'biobehavioral synchrony' [37,41], which is the co-wiring of parent's and infant's brains and behavior into a synchronous unit that supports the infant's brain growth and buttresses social competencies (see Glossary). Oxytocin has a critical role in neural plasticity at both the molecular and network assembly levels due to its unique mode of release from both oxytocin-producing hypothalamic sites and dendrites, which enable a long half-life, activity at locations distant from receptors, and experience-dependent network reorganization leading to autoregulated release in response to attachment cues [42–45]. In humans, oxytocin functionality is transferred from parent to child via repeated experiences of social synchrony during parent-infant interactions, that is, the matching of parent's and infant's behavior in the gaze, touch, affect, and vocal modalities, an experience that ushers the development of children's social competencies [46–49].

Imaging studies of the human parental brain

Investigations into the human parental brain typically used fMRI to test parents' brain response to auditory, visual, or multimodal infant stimuli, such as infant pictures, movies, or sounds of infant cries, often comparing 'own infant' to a standard infant or control condition. A literature search located 46 such empirical studies (see descriptions of sample size, infant and/or child ages, stimuli, and findings in the supplementary material online). Within this modest body of research, most studies examined mothers [20,34,50–77], few tested fathers [29,51,72,78–83], and several examined nonparents' brain response to infant cues [55,79,84–92].

Using fMRI, several brain areas in human adults were repeatedly shown to activate in response to these infant cues, charting a global 'parental caregiving' network that integrates functioning of several interconnected, and at times overlapping, networks that underpin parental care (Figure 1). Similar to rodents, the three critical nodes of the human subcortical-limbic parenting network are the

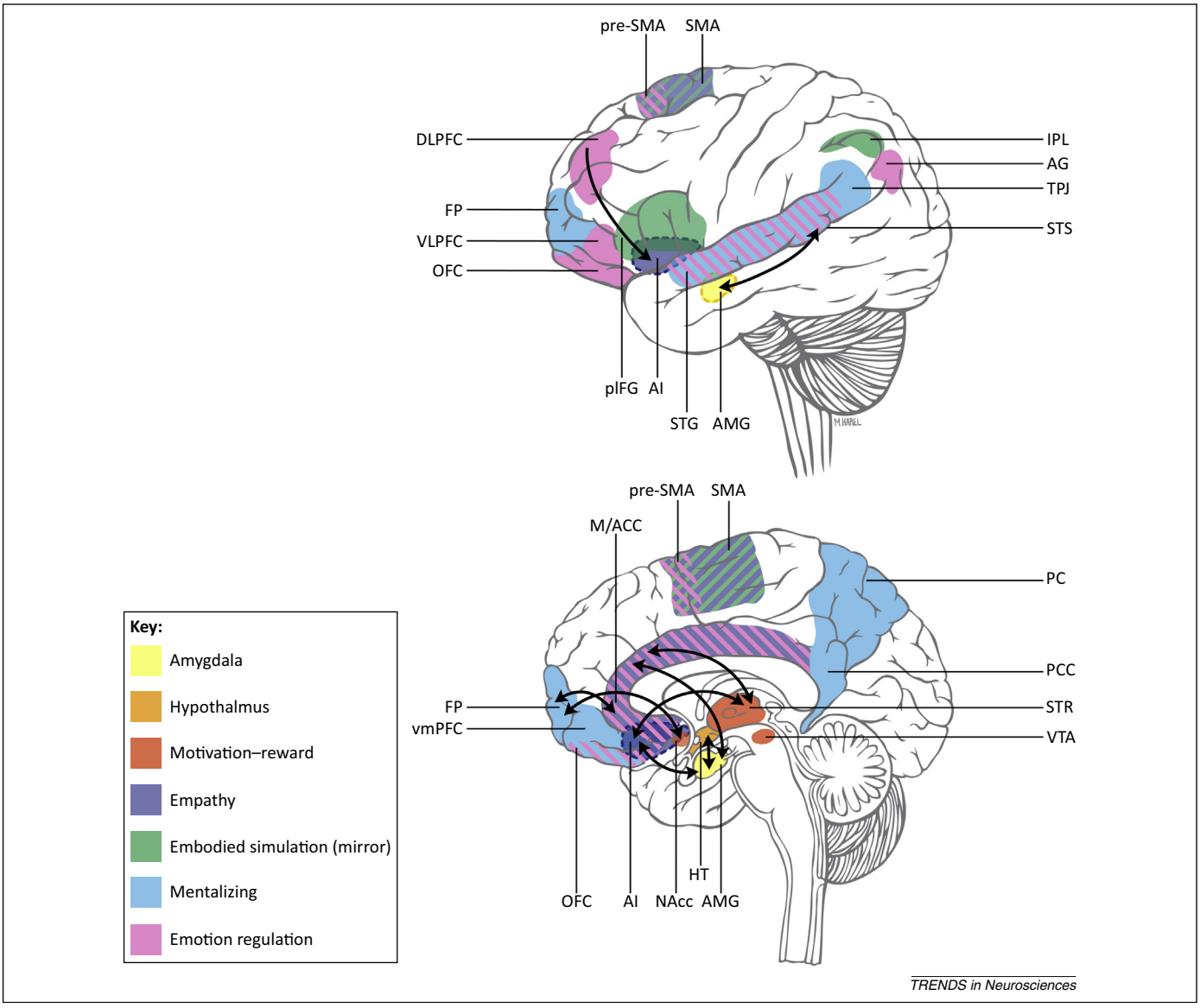

Figure 1. The human parental caregiving network. **(A)** The amygdala, a central node of the parental brain in humans and mammals, is reciprocally connected to mesolimbic dopaminergic pathway (reward and/or motivation) and insula-cingulate regions (empathy network) and is considered the core region of the 'emotional brain' [25–27]. **(B)** The reward and/or motivation subcortical network includes structures of the dopamine mesolimbic [nucleus accumbens (NAcc) and ventral tegmental area (VTA)] and nigrostriatal [substantia nigra (SN) and striatum] pathways supporting approach orientation and the incentive value of infants [22,24,93]. **(C)** The hypothalamus contains oxytocin-producing nuclei and projects to the amygdala and subcortical reward network, creating a limbic network implicated in mammalian caregiving that underpins parental vigilance and motivation [18,22–24,36,94,95]. **(D)** The empathy network includes the dorsal anterior cingulate cortex (ACC), anterior insula (AI), and supplementary motor area (SMA), which resonate with physical pain and emotional distress of others [96–98]. **(E)** The embodied simulation (mirror) network comprises sensorimotor and pre-sensorimotor areas, inferior parietal lobule (IPL), and inferior frontal gyrus (IFG), and is involved in perception–action coupling, action understanding, and imitation [100,103]. **(F)** The mentalizing network comprises temporoparietal and frontal regions, including superior temporal sulcus/gyrus (STS/STG), temporal-parietal junction (TPJ), temporal pole (TP), precuneus, posterior cingulate cortex (PCC), and ventromedial prefrontal cortex (vmPFC), and subserves mental-state understanding and perspective-taking [96]. **(G)** The emotion-regulation network supports multitasking and executive control, and includes the dorsolateral prefrontal cortex (dlPFC), medial orbitofrontal cortex (mOFC), middle frontal gyrus (MFG), and frontopolar cortex [102]. Subcortical structures (amygdala, hypothalamus, and limbic reward) are connected via ascending and descending projections to cingulo-insular structures (AI and ACC) to enable resonance with infant physical pain and affective state, and with cortical networks supporting parent–infant action coordination (embodied simulation), understanding infant signals (mentalization), and multitasking and action inhibition (emotion regulation). Connections among structures within each network and among cortical networks support parents' ability to translate moment-by-moment affective resonance to future planning, select among behavioral options, and inhibit distraction to serve long-term goals.

amygdala, oxytocin-producing hypothalamus, and dopaminergic reward circuit, including both the mesolimbic (NAcc, VTA) and nigrostriatal [striatum, substantia nigra (SN)] pathways [93], thereby underscoring the highly conserved nature of parental care across mammalian evolution. These structures not only maintain close interconnectivity, but are also connected via multiple ascending and descending projections to paralimbic and cortical networks implicated in empathy, embodied simulation, mentalizing, and emotion regulation [94–97]. Such connectivity allows the integration of later-evolving structures implicated in higher order socioaffective processes with the conserved, automatic brain circuitry underpinning maternal care. Functioning of these cortical networks enables parents to resonate with infant state through the empathy network, which includes structures of the anterior insula–cingulate cortex [anterior insula (AI) and anterior cingulate cortex (ACC)] that help parents: (i) respond to infant pain and emotion by representing it in themselves [98]; (ii) ground experience in the present moment, possibly via the activity of spindle-shaped 'von economo' neurons, which are among the pyramidal neurons in layer 5 connecting limbic and motor structures and are hypothesized to permit fast, highly integrated representations of emotional moments [99]; (iii) afford perceptual-motor coupling and embodied simulation of infant action in the parent's brain via the mirror neuron system [inferior parietal lobule (IPL), inferior frontal gyrus (IFG), and supplementary motor area (SMA)] [100]; (iv) understand nonverbal signals and infer infant intentions through the mentalizing network [superior temporal sulcus/gyrus (STS/STG), precuneus, posterior cingulate cortex (PCC), temporal parietal junction (TPJ), and ventromedial prefrontal cortex (vmPFC)] [97,101]; and (v) engage in multitasking, arousal and emotion inhibition, and action selection to accommodate long-term goals utilizing the latest evolving emotion regulation and/or executive network [frontopolar cortex, dorsolateral prefrontal cortex (dlPFC), medial orbitofrontal cortex (mOFC), and middle frontal gyrus (MFG)] [102]. These cortical networks, jointly defining the human 'social brain' [103], are overlapping, serve multiple functions, and are superimposed upon the ancient limbic circuits that provide immediacy and nonconscious motivation to the interoceptive and conscious aspects of parenting.

The human parental brain as a flexible platform for evolutionary adaptation

Expansion of mammalian caregiving structures into a global, overlapping, multifunctional human parental care network gives rise to the hypothesis that the human parental brain did not evolve by integrating networks subserving complex social functions (theory-of-mind, empathy, or emotion regulation) into the parental context, as often conceptualized [20,104–106], but rather those structures evolved in *Homo sapiens* within the parental context to maximize infant survival in harsh environments. Such adaptations transferred the human brain from the automaticity of mammalian caregiving to the flexibility of human parenting by evolving structures that can represent others' states in one's brain (embodied simulation), resonate with nonverbal signals (empathy and mentalizing), and hierarchically organize tasks (emotion regulation) to safeguard infants from harm. Thus, I hypothesize that the human did not foreshadow the parent but rather the parent prefigured the human. This brain evolution may have been enabled by high circulating oxytocin levels following childbirth [97], increased brain plasticity during this period [28], and the unique opportunities for biobehavioral synchrony embedded in maternal–infant bodily contact [107]. Flexible integration of ancient with later-evolving networks also afforded immense cultural variability in human parenting, permitting each culture to uniquely combine primary survival and/or reward functions with complex cultural meaning systems, while adapting to ecological constraints and balancing multiple caregivers' roles, thereby demonstrating how the parent–offspring interface generates a flexible platform for evolutionary adaptation [108].

Brain response to infant cues depends on stimulus type and parent gender

Activation of specific networks within the parental brain is modulated by stimulus type and parental sex. Table 1 describes the degree of activation of each network according to research participant (mother, father, or nonparent) and infant stimuli (auditory, visual, or multimodal cues). Findings pinpoint several interesting directions. First, remarkable similarity has emerged in brain activation to infant pictures in mothers, fathers, and nonparents, and all studies involving infant visuals reported activation of the motivation-reward limbic network. Seeing infants appears to elicit motivation to care in all adult members of the species, which may have functioned to enhance infant survival throughout human history when many mothers died at childbirth, thus leaving infants to nonparental care. Such findings suggest the existence of an 'alloparental caregiving' network that can flexibly activate in all adults via bottom-up processes, where nonparents assume responsibility for infant care [109]. Second, the 'mammalian' parental network described in rodents, centering around the oxytocin-producing hypothalamus [MPOA, bed nucleus of the stria terminalis (BNST), and lateral septum (LS)], is rarely activated in human mothers, was not found to activate in nonparents, and is minimally observed in studies of fathers in response to infant pictures and cry stimuli, indicating that human caregiving relies to a greater extent on associative and sociocognitive structures. The amygdala activates more to infant crying than to pictures and more in mothers than fathers and nonparents, consistent with its conserved vigilance role [25,27,72]. Finally, although all father studies reported activation of the mirror network, not all mother studies did. These findings highlight two distinct pathways to the parental brain: the maternal pathway operating via conserved salience-detection and subcortical structures sensitized by pregnancy hormones, and the paternal pathway formed on the basis of experience through cortical networks that support perceptual-motor coupling and representation of the infant's state in the parent's brain [72].

The maternal and the paternal brain: plasticity, connectivity, and correlates

Active paternal care is observed in only 3–5% of mammalian species, and father care in these species is facultative,

Table 1. Parental brain networks activated by study group and by infant cue type[a,b]

Networks activated	Mothers		Fathers		Non-Parents	
	Crying (*N*)	Pictures and/or movies (*N*)	Crying (*N*)	Pictures and/or movies (*N*)	Crying (*N*)	Pictures and/or movies (*N*)
	5	15	2	6	5	5
Cortical and/or paralimbic networks						
Embodied simulation (mirror) network: IPL, IFG, pre-sensory-motor area	+	++	+++	+++	+	++
Mentalizing network: STS/G, TPJ, TP, PCC, vmPFC, precuneus, frontopolar cortex	++	++	++	++	+	+++
Empathy network: AI, ACC, SMA	+++	+++	+++	++	++	+++
Emotion regulation network: mOFC, dlPFC, MFG, frontopolar cortex	+++	++	X	++	+	+++
Subcortical networks						
Arousal and/or vigilance network: amygdala	+++	++	++	+	+++	+
Motivation/reward limbic network: VTA, Nacc[c], striatum, SN, GP[d]	+++[a]	+++[a]	+++[b]	+++[b]	+	+++
Mammalian parenting network: hypothalamus, BNST[e], LS, caudate nucleus, MPOA[c]	+	++	X	+	X	X

[a]*N* = 38 studies.

[b]Data represent results of fMRI studies of brain response in healthy adults to auditory (crying), visual (pictures), or multimodal (movies) infant cues using own-infant > other-infant or infant > control contrasts. X, Not found; +, sometimes found; ++, mostly found; +++, always found. Abbreviations: GP, globus pallidus; TP = temporal pole.

[c]Found mostly in mothers.

[d]Found mostly in fathers.

[e]Part of network but rarely found in human studies.

that is, enhances infant survival in the context of mothering [110]. Thus, further research is needed to describe not only mechanisms that shape the paternal brain, but also those that enable mothers and fathers to coordinate effort to jointly raise their young and those that describe the unique effects of father care on infant thriving. Research in biparental rodents demonstrated lower information processing in infants deprived of paternal care [111] and showed that active paternal care enhanced integration among fathers' brain networks implicated in nurturance, learning, and motivation [112], highlighting links between fathers' brain plasticity and active caregiving.

Only two studies compared mothers' and fathers' fMRI responses in the same study. Both found greater amygdala activation in mothers and greater cortical activation in fathers, supporting the distinct pathway hypothesis. In the first study [51], mothers' and fathers' brain activations in response to their infant's video were tested for correlations with oxytocin and vasopressin levels (hormones uniquely associated with female and male bonding [36], respectively) and for brain-to-brain synchrony. The amygdala revealed different correlations, with oxytocin in mothers and vasopressin in fathers, corroborating animal findings (Figure 2).

The second study [72] attempted to tease out parents' sex from the primary and/or secondary caregiving role by recruiting three groups of first-time parents: mothers (primary caregivers), heterosexual fathers (secondary caregivers), and primary-caregiving homosexual fathers raising infants within a partnered relations without maternal involvement. In all parents, infant cues activated multiple parental brain areas, including structures in all aforementioned networks. Also, for the most part, differences did not emerge between primary and secondary caregivers regardless of sex. However, mothers showed greater amygdala activation (a fivefold increase), whereas secondary-caregiving fathers revealed higher activation of the STS, a key structure of the mentalizing network. Primary-caregiving fathers showed high amygdala activation resembling mothers, alongside high STS activation, similar to the secondary-caregiving fathers. Moreover, only among the primary-caregiving fathers group was functional connectivity found between the amygdala and STS, indicating that the paternal pathway recruits the maternal pathway to increase infant survival in the mother's absence. Furthermore, when testing all fathers for the connectivity discovered in the group of primary-caregiving fathers, it was discovered that the amount of time fathers spent in direct childcare correlated with the degree of amygdala–STS connectivity. Therefore, functional connectivity may operate as a plasticity mechanism by co-wiring several parenting-related structures to accommodate the father's growing involvement in childrearing [72,82] (Box 1).

In addition to functional connectivity, another mechanism by which the parental brain fine-tunes to caregiving involves increases in grey-matter volume, manifested in mothers and fathers from the first to the fourth months postpartum in a longitudinal study. Interestingly, multiple areas show comparable grey-matter increases in mothers and fathers; yet, only fathers exhibit grey-matter decreases in the OFC, PCC, fusiform gyrus, and insula, suggesting the need to fine-tune cortical control in men to enable paternal care [34,78]. Finally, a third mechanism of

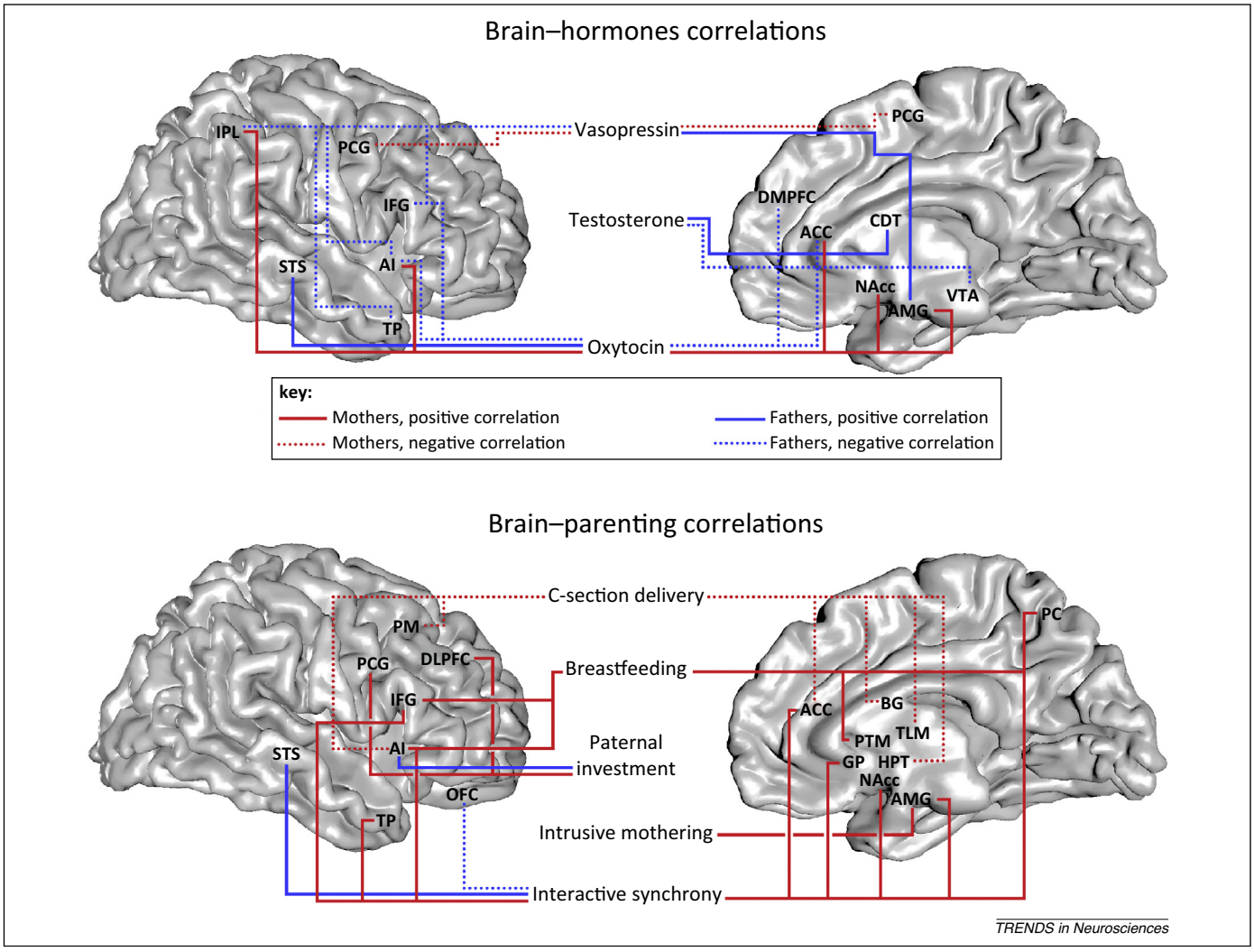

Figure 2. Brain–hormone and brain–behavior associations in mothers and fathers. **(A)** Brain–hormone correlations emerged between maternal peripheral oxytocin (plasma and/or saliva) and activation in limbic and cortical structures in empathy and mirror networks [51,69,72]. Fathers' oxytocin correlated positively to mentalizing and negatively to emotion regulation structures [51,72,79]. Vasopressin correlated with paternal amygdala [51], and testosterone correlated negatively with paternal reward structures [79,80,83]. **(B)** Brain–parenting correlations reveal that maternal sensitivity and/or synchrony correlated with amygdala and reward limbic structures and areas in the mirror, empathy, and mentalizing networks [50,51,63,71,72,75]. Breastfeeding increased activation in these networks [75], whereas having had a caesarean section correlated with lower activation [74]. Father investment and sensitive and/or synchronous parenting correlated with greater activation in empathy and mentalizing networks [72,78,83].

plasticity (brain-to-brain synchrony) was found in the aforementioned study of mothers and fathers' brain response to their own infant video [51]. Mother–father brain synchrony emerged in a functional network originating in AI and including areas in both mirror and mentalizing networks. Thus, mothers and fathers fine-tune their brain response to each other in networks supporting online understanding of infant signals to coordinate efficient caregiving, and such brain-to-brain coupling possibly had a role in the evolution of the human family (Box 1).

More recently, studies have begun to explore not only activation levels, but also their correlates, particularly hormones implicated in parental care and parenting behavior. Findings have linked networks in the parental brain to factors with known long-term impacts on infant development, including sensitive and/or synchronous parenting, breastfeeding, or neuroendocrine systems with cross-generation transmission of functionality [38,48] (Figure 2). Higher maternal peripheral oxytocin was found to correlate with greater activation in subcortical structures of reward (NAcc) and vigilance (amygdala) as well as with empathy (AI and ACC) and mirror (IPL) networks. Although the correlational nature of the data precludes ascertaining whether higher oxytocin caused greater brain activation or vice versa, data do suggest that brain and hormones render mutual influences. In fathers, oxytocin correlated with higher activation in mentalizing and lower activation in emotion regulation networks, echoing the grey-matter findings. Intranasal oxytocin administration to non-mothers increased functional connectivity between amygdala and OFC, ACC, hippocampus, and precuneus in response to infant crying [88], reduced activation in the amygdala to infant crying and laughter, and increased activation in the insula and inferior frontal gyrus to infant crying [85,88], highlighting the modulatory role of oxytocin on amygdala-cingulo connectivity and its effect in enhancing empathy to pain and emotions in the context of infant stimuli [85,88,94–97]. Fathers' testosterone, known to

Box 1. Measuring neural plasticity in the human parental brain

Human parenting is associated with the reorganization of neural networks, which suggests brain plasticity. This is consistent with the increased brain plasticity and neurogenesis reported in rodents [28]. Human parents' brain plasticity is sensitive to multiple parenting determinants, including parental hormones, parent–child interactions, parental investment, and psychopathology. Brain plasticity has been demonstrated through three main techniques that describe how the parent's brain fine-tunes to infant-related stimuli.

Functional connectivity

Functional connectivity indexes the co-activation of two or more brain structures to support parental care or in response to infant stimuli.

Parenting increases network connectivity

Fathers who assumed a primary-caregiving role showed greater connectivity compared with secondary-caregiving fathers between the amygdala and STS (mentalizing network), indicating greater co-activation of the 'maternal' and 'paternal' pathways to parenting [72]. Mothers who demonstrated more interactive synchrony with their infants revealed greater connectivity between NAcc (reward) and mentalizing, mirror, and empathy networks, indicating that the conscious aspect of parenting is underpinned by reward motivation. By contrast, mothers displaying intrusive caregiving exhibited connectivity between the amygdala and these networks, pointing to more anxious and/or vigilant underpinning of maternal care [50].

Oxytocin administration alters functional connectivity to infant stimuli

In nonparents listening to infant laughter, oxytocin increased the connectivity of the amygdala with the hippocampus, precuneus (mirror), and OFC (emotion regulation). This suggests that higher levels of oxytocin, found in mothers and fathers during the postpartum period [88], reorganize adults' brain toward infant cues.

Resting-state connectivity is observed in healthy, but not depressed mothers

Resting-state functional connectivity indexes the integrity of basic functions [39]. In postpartum mothers, amygdala was functionally connected to PCC (empathy network), enabling automatic vigilance cues to translate into maternal representation; however, the connection was decoupled in mothers with postpartum depression [54].

Grey-matter volume increase

An increase in grey-matter volume indexes plasticity in brain areas that are critical for caregiving, as seen in longitudinal studies of mothers' and fathers' brain from the first to fourth month postpartum

Mothers

An increase in grey matter was found in subcortical structures (amygdala, hypothalamus, thalamus, and SN) and in the following cortical networks: PFC (emotion regulation), precentral and postcentral gyrus, and IPL (mirror). Grey-matter increase correlated with positive perception of infant and caregiving [34].

Fathers

An increase in grey matter was found in amygdala, striatum, hypothalamus, subgenual cortex, lateral PFC, and STG. Grey matter was decreased in OFC, PCC, fusiform gyrus, and insula. A decrease in OFC correlated with more paternal behavior [78].

Brain-to-brain synchrony

Brain-to-brain synchrony indexes simultaneous brain activation in mother and father in the context of infant stimuli.

In response to their own infant's video, mothers and fathers synchronized brain activity in the right insula, which was functionally connected to activations across the social brain, including the ACC, motor and premotor areas, IFG, IPL, and mPFC. Thus, mother and father coordinate brain response online in networks implicated in understanding nonverbal infant signals toward efficient parenting [51].

decrease in men at the transition to fatherhood [113], correlated with lower VTA activation and higher left caudate activation [80,83]. Such findings coincide with the hypothesized shift in resources from mating to parenting when men become fathers [114], and with studies linking lower paternal testosterone to increased caregiving behavior in the gaze, touch, and vocal modalities [113,115].

Maternal sensitivity and synchrony, indexing mother's online adaptation to infant social signals, correlated with both subcortical reward and vigilance structures and areas in the empathy, mirror, and mentalizing networks, indicating involvement of the entire neuro-axis in the mother's behavioral responsivity to her child. Father's interactive synchrony was again linked with cortical, not subcortical structures, further attesting to the later-evolving pathway to paternal care. To date, it is not known how cultural variability in parenting is implemented in the brain or how conditions such as extended versus nuclear living, co-sleeping, grandparental care, or traditional versus egalitarian sex roles shape parents' brain during this plastic period (Box 3).

Finally, research is beginning to address the effects of adversity on a mother's brain; several studies have examined brain response in postpartum depression, trauma, or substance abuse [54,56–59,63,67,76,77]. Overall, studies suggest that psychopathology is expressed in the brain along four lines: (i) as reduced activation to infant cues, particularly in reward and empathy circuits, found in maternal depression and linked with lower maternal sensitivity and reward from parenting [54,58,59,63,76,77]; (ii) as increased vigilance, expressed in higher amygdala activation and observed in anxious, intrusive, or traumatized mothers [50,67]; (iii) as reduced and/or altered connectivity, expressed as decoupling of typical connectivity, such as between amygdala and PCC [54], suggesting limitations on plasticity; and (iv) expressed in areas outside the 'parental care' network, for instance lower hippocampal activation in traumatized or substance-abusing mothers [57], suggesting disruptions in the formation of attachment-related memories. Inasmuch as the brain basis of pathological parenting has received extremely little research attention, substantial further study is required to describe how various adverse conditions may shape distinct, pathology-specific profiles that can be identified early in life to design targeted early interventions.

Parent's brain and child's social development: processes of biobehavioral synchrony

The mammalian parental brain evolved in the context of mutual influences between maternal and infant physiology through development of the placenta as a co-regulated core of maternal–fetal effects and the subsequent emergence of thalamocortical networks shaped by pregnancy hormones [116]. Mutual postbirth influences occur via processes of biobehavioral synchrony: maternal regulation of the infant's immature systems via specific regulatory elements embedded in the mother's body (body-heat, touch, smell, heart rhythms, and lactation), where each maternal

element corresponds to a distinct environment-dependent system in the infant (stress response, biological clock, attention, and exploration) and, in turn, is sensitive to input from the child (Box 2). Humans are the most premature of all species; whereas *Macaca* newborns display 70% of adult brain size at birth and chimpanzees display 40%, human neonates reveal only 25% [117]. Greater immaturity in the infant's brain at birth requires longer period of maternal care; thus, human infants remain open for an extended period of plasticity to parental provisions [118,119]. During this lengthy co-dependence, the parent's and infant's brains become mutually attuned, and this synchronous biobehavioral matrix builds the child's lifelong capacity for intimacy, socio-affective skills, adaptation to the social group, and the ability to use social relationships to manage stress [37,38,120].

Research has yet to examine longitudinal associations between parental brain responses to infant cues and children's later development (Box 3), but evidence supports the hypothesis that the human parental brain marks an evolutionary apex and supports the infant's ultimate ability to parent the next generation. Figure 3 describes the cross-generational transfer of human social affiliation from parent to infant across the lifespan and the role of the parental brain in this process. Such long-term impact on infant development is moderated by three critical factors that shape, and are shaped by, the parental brain: oxytocin, parent behavior and/or synchrony, and maternal–newborn physical contact.

Parental oxytocin during the first months of life longitudinally predicts children's social engagement, friendship relations, and empathy [121]. Administration of oxytocin to parents resulted in a rise in the infant's oxytocin levels [122], and parental affectionate touch increased the infant's oxytocin [48]. The mutual influences of the parent's brain on parental oxytocin and, consequently, on consolidation of the infant's oxytocin system, charts one pathway by which the parental brain carries long-term effects, consistent with findings in animals [123]. Furthermore, formation of the three affiliative bonds in humans (parental, pair, and filial) which in humans involve close friendships, are underpinned by the oxytocin system, are expressed through synchronous social behavior between partners, and are built on reciprocal parent–infant relations in infancy [124–127]. These later synchronous relations are acquired in the context of the

Box 2. Biobehavioral synchrony and the human parental brain

A central factor in the survival and thriving of social species is the ability of members to join efforts toward collaborative goals. During the early 20th century, entomologists were among the first to describe processes of biobehavioral synchrony, that is, the online coordination of biological signals (neural firing and hormonal release) and behavioral signals (leg movement and wing flapping), as being central for binding members to the social group and for executing social goals [11,17].

With the evolution of mammals, processes of biobehavioral synchrony by which young members are initiated into the social milieu became acquired within the 'nursing dyad' through maternal–infant synchrony. The mother's body contains physiological, hormonal, and sensory cues that are coordinated online with the infant's and that provide a maturational context for the infant's environment-dependent systems (biological clock, autonomic functioning, and stress response). Maternal species-typical behavior shapes infant's oxytocin and glucocorticoid receptor distributions, exerting a lifelong impact on stress management and social affiliation [37,107,123].

Human studies indicate that social synchrony (the online coordination of social behavior between parent and infant in the gaze, vocalization, affect, and touch modalities) triggers biological synchrony between the parent's and child's physiology [37,38,41]. During synchronous moments, the parent's and infant's heart rhythms [145] and oxytocin levels [48,115] synchronize.

Social synchrony provides a critical environmental input for the human infant during a sensitive period at between 2 and 9 months of age [37,38]. Longitudinal studies indicate that social synchrony predicts emotion regulation, self-control, attachment security, stress management, and empathy across childhood and adolescence [121,125–132,134].

Primate and human brains contain networks that resonate in real time to the states, actions, and emotions of conspecifics. Such systems show brain-to-brain coupling when humans synchronize motor action [146] or when mother and father are exposed to their infant [51]. Although human studies have yet to show synchronous fMRI responses in parents and infants, evidence suggests brain-to-brain synchrony in adults [147]. Synchrony may fine-tune the child's social brain to the social group, enable child mastery of social rules, and help children become members of their own culture.

Box 3. Outstanding questions

- Direction of effects in human imaging research: because human studies are correlational, it is still unknown whether activation of the 'parental caregiving network' leads to expression of parenting behavior or whether, vice versa, engaging in parent–child interactions sensitizes activity in the parental brain.
- Longitudinal effects of the human parental brain: to date, no study has followed developmental outcomes in children in relation to parents' brain response in infancy. The proposition that such continuity exists and is mediated by contact, synchrony, and oxytocin (Figure 3, main text) has yet to be empirically validated.
- Development of the parental brain across childhood and adolescence: much further research is required to examine changes in activations and connectivity of specific networks in the parental brain from infancy to childhood to adolescence.
- Brain-to-brain synchrony: synchrony between parent's and infant's brains as measured by two simultaneous fMRIs has not yet been demonstrated, although evidence suggests the existence of such synchrony (Box 2, main text).
- Parent's brain and psychopathology: studies are beginning to explore the parental brain in specific psychiatric conditions, such as postpartum depression or post-traumatic stress disorder, but much further research is required to describe 'neural signatures' of specific psychopathologies.
- Change in parental brain following intervention: researchers would do well to examine how amenable the parental brain is to early interventions that increase physical contact or sensitive parenting.
- Adoption and the maternal brain: the study of fathers indicated that the adoptive primary-caregiving father's brain did not differ from that of the biological primary-caregiving father; yet, no research has examined the brain of adoptive mothers, its developmental course, and its sensitivity to child age at time of adoption.
- Cultural variability and the parental brain: research should investigate how culture-specific living conditions and childrearing philosophies are implemented in the parent's brain, including co-sleeping, traditional versus egalitarian sex roles, nuclear versus extended family living, or culturally accepted levels of eye-gaze and touch during social contact.
- Role of parent–child interface in evolutionary adaptation: the contribution of the parental–infant context to human evolution of unique abilities is among the most intriguing open questions in research on the adaptive parental brain.

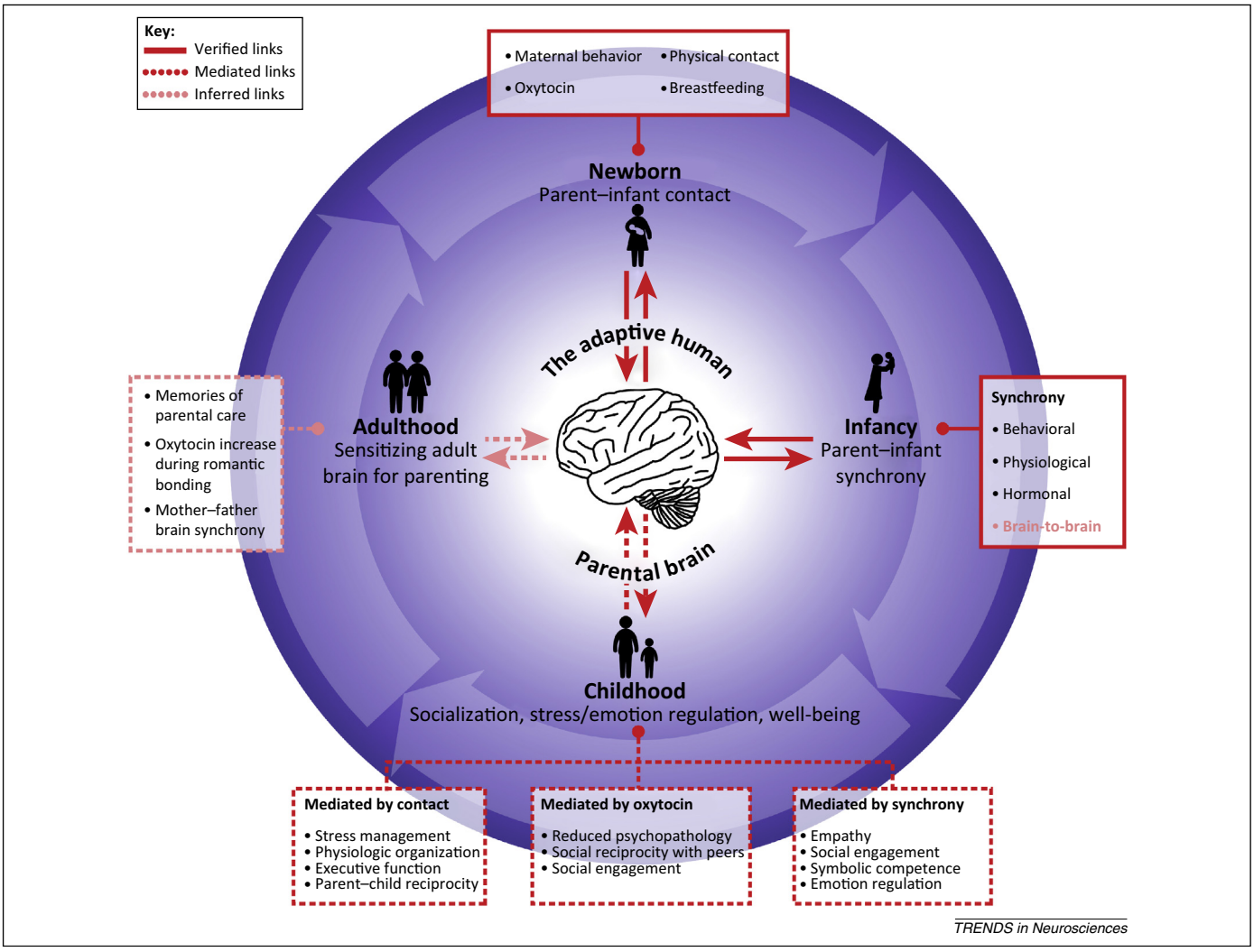

Figure 3. Long-term impact of the adaptive human parental brain on children's social development. Presented in the figure are links supported by previous research (red solid line), links via mediating variables (red-dotted line), and inferred links on the basis of current evidence (pink-dotted line). In the newborn period, parent brain shapes, and is shaped by, oxytocin, breastfeeding and/or contact, and parenting behavior [34,75,78]. In the infancy stage, the parent brain is mutually related to parent–infant synchrony, parental hormones, and paternal investment [50,51,69,71,72,79–81]. During childhood and/or adolescence, while studies have not tested longitudinal relations between parental brain in infancy and child outcomes, long-term effects of oxytocin, synchrony, and maternal–newborn contact have been demonstrated [37,38,46,121,125–130,132,134]. Aspects of adult affiliative biology that prepare individuals for the parental role originate in systems associated with the parental brain, charting a hypothesized link between parent brain response to infant cues and the child's ultimate capacity to parent the next generation. These include recollections of parental care in childhood, [56,69,92], the response of the oxytocin system to pair-bonding and parenting [47,48,115,124], and brain-to-brain synchrony between adults in attachment contexts [51].

parent–infant biobehavioral synchrony, consistent with Bowlby's attachment theory [128].

A second pathway of longitudinal effects involves parents' synchronous behavioral style that is sensitive to infants' moment-by-moment signals. Extant research demonstrated that sensitive parenting in infancy favorably impacts social outcomes across childhood and up through adulthood [129], including diminished psychopathology, social adaptation, empathy, emotion regulation, and creative-symbolic thinking [125–130]. Finally, maternal–newborn physical contact and breastfeeding chart a third pathway of continuity from the parental brain by supporting cognitive development, better stress management, and improved health [74,75,131,132]. Thus, the adaptive human parental brain stands at the center of the cross-generation transfer of human sociality, supporting infant long-term adaptation to life stresses and the transmission of affiliative biology from parent to offspring [36,37]. The centrality of the parental brain for infant social development suggests that interventions aimed at promoting parent–newborn contact or interactive synchrony may carry long-term effects on infant social competencies via enhancing parents' brain response to their infant and enabling brain-to-brain synchrony [38].

The parental brain and human sociality: implications for theory and research

How can research on the parental brain expand our understanding of human sociality? First, because all mammals parent their children, parenting is the only aspect of social neuroscience that can be studied across the evolutionary ladder utilizing a comparative framework that applies direct mechanistic hypotheses based on animal research to the human social brain. Such comparisons are not easily accomplished in other human-specific functions, such as empathy or emotion regulation. Second,

the three legs of the neurobiology of parenting (brain structures comprising the parental caregiving network, oxytocin, and social behavior in the gaze, vocalizations, and touch modalities) were found to underpin most, if not all, human social functions throughout life, including group cohesion [133], affiliation [36,41,134], empathy [121,135], and theory-of-mind [136]. Disruptions to these components were repeatedly linked with psychopathologies involving social dysfunction, such as autism, social anxiety, depression, or schizophrenia [46,137–140].

Finally, the parental brain provides a unique setting for tapping into critical issues in social neuroscience. It has been argued that social neuroscience must move from assessing lab-based paradigms to testing real-life situations, ecologically valid paradigms, and dynamic social exchanges [141]. Research on the parental brain, particularly studies utilizing infant videos in the home ecology and testing online brain response to parent–child interactions, can uncover how the brain ascribes salience to social stimuli, encodes attachment cues, and sensitizes neuroendocrine systems to self- and culture-relevant social phenomena. Assessing such patterns in relation to the child's long-term development can offer new insights into the origins of human sociality.

Another unresolved issue in social neuroscience is the need to shift research from the functioning of a single brain to the coordination of several brains, to understand how brain-to-brain synchrony enables formation of social bonds and collaboration among groups [141,142]. Such collaborative abilities involving the synchronous functioning of several brains in pursuit of joint goals have long been suggested to underpin the success and thriving of social species, including *Homo sapiens* [143]. Animal studies demonstrated that biological synchrony tightens under survival-related conditions [144], of which parental safeguarding of vulnerable infants is prototypical. The 'situated' parental brain, constantly updating information in response to changing contextual demands and expanding abilities to protect infants from harm, provides a dynamic, plastic, and adaptive model for studying how the brain of one human synchronizes with that of another toward the ultimate social goal: the successful rearing of infants to become adaptive members of the human family.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tins.2015.04.004.

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