Impact of Brain Evolution on Hormones and Social Behaviour

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Summary

In mammals, the social behaviour of males and females reflects their different lifetime reproductive strategies. Reproductive success in males is determined by the outcome of competition with other males, the dominant males mating with as many females as possible. Hence, males rarely form strong social relationships and male coalitions are typically hierarchical, with emphasis upon aggressive rather than affiliative behaviour. Females have a different strategy. They invest in the production of relatively few offspring, with reproductive success being determined by the quality of care and the ability to enable infant survival beyond the weaning age. Females, therefore, form strong social bonds with their infants and their female-female relationships are affiliative, especially among matrilineal kin who often assist with infant care. In a minority of mammalian populations (less than 5%), a promiscuous male strategy is not an option, owing to the low population density of females. In this situation, males and females form a partner preference (bond), defending their partners against intruders and both parents participating in infant care (Kleiman 1997). The questions addressed in this chapter concern the hormonal mechanisms that underpin these female-bonded social relationships and how the evolutionary development of the neocortex in large-brained primates has impacted on the role of "bonding" as being an integral adjunct of physiological homeostasis.

Introduction

The neural template for hormonal influences on social behaviour has been thoroughly investigated in small-brained mammals. Considerable attention has been given to the monogamous vole and the role of the neurohormones, oxytocin (OT) and vasopressin, in activating the reward mechanisms of the brain that are involved in establishing partner recognition and selective bonding. However, monogamy is relatively rare among mammals, and a more appropriate starting point for understanding social relationships at a mechanistic level is in the conserved mechanisms that underpin the reciprocal

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bonding between mother and infant. Many mammalian adaptations have evolved, including placentation milk provisioning, homeothermy and intensive maternal care, to ensure the mother-infant bond has become a very significant biological relationship. The high levels of prenatal resource investment by female placental mammals and their unique ability to produce milk devolved the priority for parental care to the female. Infants were rendered special to females by the deployment of brain reward mechanisms that were linked to hormonal state and recognition systems, primarily olfactory, that ensured the successful nurturing of offspring.

The placenta has made a notable contribution to the way hormones shape the mother-infant relationship. The placenta is an endocrine organ in its own right, and through production and regulation of hormones by the placenta, the foetus determines its own destiny (Keverne 2006). Progesterone is the steroid hormone that dominates pregnancy and primes the female brain for promotion of maternal behaviour, increased maternal feeding and suppression of sexual behaviour (Fig. 1). Oestrogen levels, which increase towards the end of pregnancy, are also indirectly dependent on the placenta for conversion of progesterone to androgen, which then serves as the precursor for aromatisation to oestrogen. Progesterone and oestrogen are steroids that readily enter the blood-brain barrier and prime the brain's OT neurons and receptors. OT is produced by the hypothalamic parvocellular neurons that activate maternal behaviour, while the magnocellular neurons produce OT that is released from the posterior pituitary and is important for parturition and milk letdown. High levels of progesterone promote OT synthesis but inhibit neural firing and hence OT release (Keverne and Kendrick 1992). Around the time of parturition, the falling levels of progesterone and increasing levels of oestrogen promote synthesis of OT receptors in the brain (Broad et al. 1999). Having been synthesised in hypothalamic neurons, OT is released in the brain at parturition to facilitate olfactory recognition of offspring and thereby promote specific maternal bonding.

Although OT-based affiliative bonding is likely to have evolved in mammals to activate maternal care and reinforce the mother-infant bond, other female affiliative interactions in rodents are also regulated by OT. In the monogamous prairie vole,

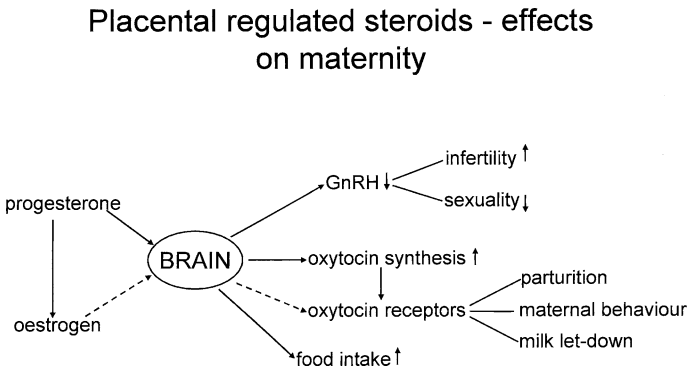

Fig. 1. Steroid hormones, notably progesterone and its aromatisation via androgen to oestrogen in the foetus, prime the brain for various components of maternalism and act directly to promote feeding and inhibit reproduction

Microtus ochrogaster, females form an enduring "pair bond" dependent on a specific olfactory partner preference induced by mating (Williams et al. 1992). A series of recent studies have demonstrated that the release of OT from the hypothalamus post-mating in prairie voles enables a female to form this exclusive olfactory partner preference (Williams et al. 1994; Lim et al. 2004b). Given that evolution is conservative, it is not surprising that many forms of social relationships have devolved from the mechanistic foundation that subserve mother-infant bonding. Indeed, there are many conserved similarities between mother-infant bonding and monogamy in prairie voles; both are triggered by an olfactory input (odour of infant or mate), both occur spontaneously after the release of OT, and both require vaginal-cervical stimulations (via parturition or mating) for this to be activated. Intriguingly, work with mice carrying mutations in the gene encoding OT confirm that this peptide hormone is crucial for social recognition, as these mutant mice are unable to form olfactory memories for conspecifics (Ferguson et al. 2000, 2001).

Olfaction and Social Reward

The brain's oxytocinergic system, together with olfactory recognition, underpins the formation of female social relationships, be they with mates, offspring or kin. The formation of these relationships requires familiarity, which for kin is brought about by prolonged contact and grooming. For completely novel stimuli, such as strange males or newly born offspring, overcoming neophobia is of some significance. It is, therefore, noteworthy that OT knockout mice that fail to form recognition memories also exhibit altered anxiety levels (Winslow et al. 2000; Amico et al. 2004). Hormones are also important in the context of mate recognition. The formation of familiar sexual relationships involves sexual activity, which can only occur when the female is in oestrus; offspring recognition requires parturition linked to the hormones of pregnancy. Both pregnancy and oestrus provide an endocrine context for the synthesis of OT and OT receptors. Oestrogen acts through the oestrogen receptors, ERα and ERβ; ERβ is expressed in the hypothalamic neurons that synthesize OT (Mitra et al. 2003), whereas ERα is required for the synthesis of OT receptors in the amygdala (Young et al. 1998). Interestingly, both ERα and the ERβ knockout mice are similarly impaired in social recognition tests, as observed in the OT knockout mice (Ferguson et al. 2001; Choleris et al. 2003). Hence, in the context of oestrus and parturition, the female's brain undergoes radical reorganisation with respect to the synthesis of OT and its receptor. The key areas of the brain associated with social recognition and preference are the olfactory bulb, the amygdala and the nucleus accumbens (Liu and Wang 2003).

Although the olfactory bulb has no oxytocinergic terminals, there is an abundance of OT receptors. This mismatch of terminals with receptors is functionally addressed by the neurohumoral release of OT into cerebrospinal fluid at parturition and mating. These significant biological events produce the changes in sensitivity, synaptic efficacy and neural firing in the olfactory bulb that are integral to the olfactory learning process for social familiarity (Keverne 1999; Brennan 2001). Hence, OT infusions into the cerebral ventricles enable social olfactory memory in rats (Dluzen et al. 2000), whereas OT infusions in the olfactory bulb reversibly influence both the frequency and the amplitude of excitatory postsynaptic currents at the reciprocal dendrodendritic

synapses important for olfactory learning (Osaka et al. 2001). Moreover, OT infusions into the amygdala, a primary relay for olfactory processing, restore the ability to make social recognition in OT knockout mice (Ferguson et al. 2001). The amygdala has reciprocal connections with the NAcc, a structure that shows enhanced levels of Fos-IR and increased dopamine (DA) transmission in rats following exposure to biologically significant odours (Pfaus and Heeb 1997). OT receptors are particularly notable in both the shell and the core of the NAcc and have been implicated, together with DA release, in pair bond formation in the monogamous female vole (Liu and Wang 2003; Fig. 2). Moreover, if the socially relevant behaviour is experienced in the same context as neutral odours, and presumably other social sensory cues, a conditioned association of these second order cues as attractive with behaviourally rewarding properties will develop (Kippin et al. 2003). This association of odour cues with social reward is facilitated in the non-monogamous species by infusions of receptor agonists for the OT neuropeptide and also for the dopamine D2 receptor, whereas OT antagonists block odour-induced partner preferences in the monogamous species (Lim et al. 2004a). Mating at oestrus provides a means of imprinting olfactory recognition of conspecifics. These sensory cues acquire behaviourally rewarding properties

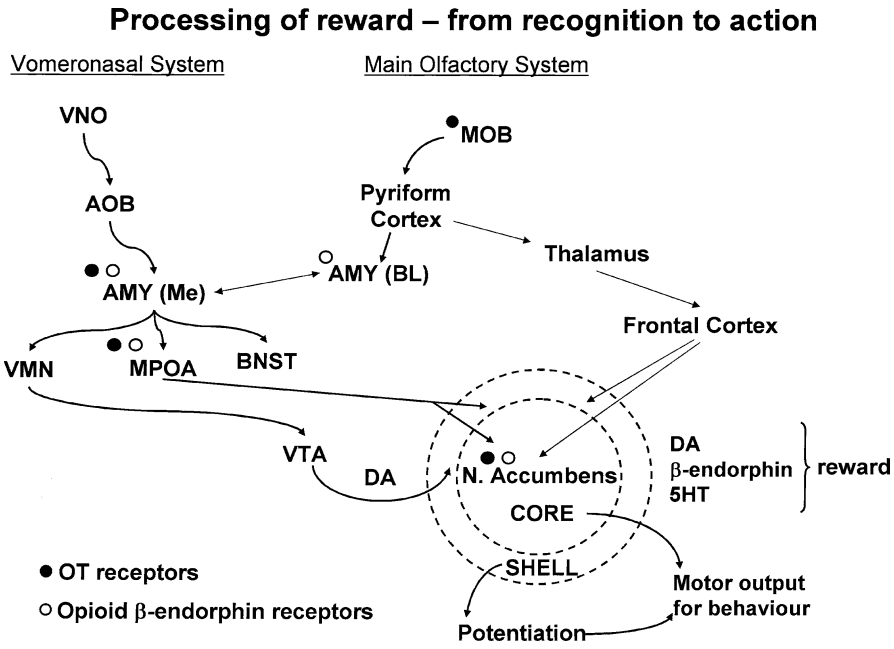

Fig. 2. The circuitry processing olfaction and pheromones is given special status by the neuropeptides regulating maternal behaviour and reward, with enhanced activity at a number of relays for this sensory input to the nucleus accumbens.
VMN – ventro-medial nucleus, MPOA – medial pre-optic area, VTA – ventral tegmental area, AMY – amygdala, **Me – Medial, (verify si bien transcript par Astrid)** BNST – bed nucleus of stria terminalis, VNO – vomeronasal organ, DA – dopamine, MOB – main olfactory bulb, AOB – accessory olfactory bulb

through connections with the NAcc, which further serves as a template for conditioning other secondary sensory cues. Hence, the expansion of features that become familiar and rewarding consolidates selective individual recognition for conspecifics with many common features and few differences. Thus a common biology linked to olfaction underpins many aspects of mammalian social behaviour in small-brained mammals.

The Role of Mammalian Olfactory Systems in Social Bonding

Olfaction is the primary sensory modality in small-brained mammals, coordinating and engaging their social behaviour. Thus, in the context of mother-infant bonding, the hormones of pregnancy induce the synthesis of oxytocin receptors in the olfactory and vomeronasal projection pathways (accessory and main olfactory bulbs, medial amygdala, and medial preoptic area; Fig. 2) as well as oxytocin and dopamine receptors in the nucleus accumbens, an area of the brain concerned with social and many other aspects of reward (Broad et al. 2006). Thus, if socially relevant behaviour occurs together with an individual's odour, a conditioned association can develop that enhances the attractiveness and memory of these familiar odours.

Small-brained mammalian rodents clearly have a well-developed sense of smell that is integral to determining sex differences in reproductive behavioural strategies (Keverne 2002). Indeed, the largest gene family in the mouse genome, >1000 out of 25,000 genes (Zhang and Firestein 2002), is given over to encoding receptors for olfactory molecules. In addition, some 300 genes code for vomeronasal receptors, which respond to non-volatile odours (pheromones), such as those odours found in urine and amniotic fluid that are key to sociobehaviour (Dulac and Axel 1995; Herrada and Dulac 1997). These receptors represent the first processing stage of the vomeronasal (or "accessory") olfactory system, which is the major pheromone chemosensory system in small-brained mammals (Brennan and Keverne 2004; Keverne 2002). This chemosensory system is distinct from the main olfactory system, which is present in all mammals and processes volatile airborne odours. However, it has been shown that a very small subset of these olfactory receptors do respond to peptide fractions (Liberles and Buck 2006), a property normally associated with vomeronasal organ (VNO) receptors. These peptides are probably binding proteins found in olfactory gland secretions and important for the transport of aquaphobic compounds through the watery mucous. The importance of the vomeronasal system for sociobehaviour in rodents, as reported earlier, has been illustrated in studies with mice carrying mutations in the vomeronasal genes coding for pheromone detection (V1r gene family; Del Punta et al. 2002) and receptor transduction (e.g., V2r gene family and V2r TRP2 ion channel; Stowers et al. 2002). Female mice lacking this VNO receptor ion channel fail to engage the behavours that illustrate mother-infant bonding. They spend little time in the nest with their offspring and fail to protect them by aggressively excluding intruders from the nest area (Kimchi et al. 2007).

Although it appears from comparative genome studies that ancestral primates could process olfactory information via the vomeronasal system, this ability became vestigial 23 million years ago in the ancestry of modern-day New World and Old World primates and apes (Liman and Innan 2003; Zhang and Webb 2003). Further evidence for

functional degeneracy comes from comparative phylogenetic analysis of the genes that encode olfactory receptors in marmoset monkeys (Whinnett and Mundy 2003). These studies have estimated from sequence disruptions that >30% of olfactory receptor genes are non-functional pseudogenes in non-human primates, rising to >60% in the human genome (Gilad et al. 2003, 2004). Coupled with these genetic changes, there has also been a dramatic reduction in the relative size of the olfactory cortex, from 65% of total cortex in insectivorous and rodent mammals to little more than 4% in Old World primates (Stephan et al. 1982).

The decline in olfactory processing has, in part, been driven by the need of large-brained Old World primates to gather their social and foraging information from visual cues as they evolved from nocturnal to diurnal lifestyles. Arguably, the most significant visual change in Old World primates was the evolution of trichromacy (Surridge and Mundy 2002; Surridge et al. 2003), which occurred at approximately the same time as the pseudogenization of the Old World primate vomeronasal genome (Webb et al. 2004). This change also coincided with the development of colourful sexual adornments that signal reproductive receptivity in females and dominance in males and a transition to vision as the dominant sensory system. Sexual behaviour was no longer restricted by oestrus and most sexual interactions became non-reproductive, but served for sexual bonding. Postpartum maternal care extended mother-infant bonding beyond the period of suckling when infant mobility required the complex visual recognition of faces at a distance. Indicative of this dramatic shift in the regulation of sociobehaviours from the reliance on olfactory information in small-brained rodents to visual information in Old World primates is the negative correlation found between the size of an area of the brain central to relaying visual information (the lateral geniculate nucleus) and that which relays chemosensory information (the olfactory bulb; Barton 1998).

These important anatomical changes in the evolutionary remodelling of the mammalian brain have been crucial to the reorganisation of reproductive strategies. In addition to the pseudogenization of vomeronasal and olfactory receptor genes, the downregulation of gonadal and placental hormones in determining sexual and maternal care has given way to an upregulation in social determinants of behaviour. Castrated male primates continue to show a sexual interest in females years after gonadectomy (Michael and Wilson 1973) but lose sexual interest within days of losing dominance and social status (Keverne 1992). Reproductive strategies are therefore very complex and embedded in social learning and the social structure of the group in which primates live. Moreover, delaying the onset of puberty and extending the period of postnatal care have enabled extensive growth and enlargement of the neocortex. In Old World female primates, unlike small-brained rodents, sexual behaviour is not restricted to a few hours determined by oestrus; neither do females require the hormones of pregnancy to become maternal. Hence, female sexual activity is not primarily reproductive since most occurs outside the fertile ovulatory period. Moreover, in the context of maternalism, non-pregnant females play an important role in infant care, which extends way beyond the infant's weaning period. Parenting and alloparenting are lifetime occupations for social living primates, an evolutionary development that has produced a profound impact on the brain.

Social Complexity, Neuropeptides and Brain Reward

Primates differ from other mammals in the complexity of their social interactions, and unlike other mammals, these interactions are not restricted to periods of prime biological significance, such as parturition and mating. Across primate taxa there are many different mating systems and affiliations, but it is the Old World monkey societies that are notably recognised for the complexity of their social organisation (Dunbar 1992). Throughout primate evolution there has been a general trend of increasing brain size relative to body size, driven largely by the requirement to process this increasingly complex social information (Dunbar 1998). For instance, baboons have both the largest relative neocortex size of any Old World primate species and the largest group size. This brain expansion has not been isometric but shows that different brain regions have evolved at different rates. In particular, the primate visual cortex has become especially enlarged, comprising up to 50% of total neocortex (Van Essen et al. 1992). It has also become increasingly complex, with several areas devoted to the differential processing of visual information such as facial expression (Perrett et al. 1992), including the evolution of some areas such as the middle temporal visual area that are non-homologous to cortical areas in other small-brained mammals (Ghazanfar and Santos 2004). The importance of vision in regulating primate social behaviour is evident from studies of feral primates, where the majority of primate social time is devoted simply to monitoring other individuals, whereas primate social group size correlates with increases in the number of neurons relaying visual information to the cortex (lateral geniculate nucleus; Barton 1998). Among the highly social Old World monkeys, it is females, rather than males, who form stable cohesive groups that are maintained over successive generations, with social rank of daughter, but not sons, being inherited from mothers (Wrangham 1980; Bergman et al. 2003). This finding is particularly well illustrated from extensive records of a 16-year study of baboons, where those females that are more social (those who are groomed more frequently by others) have higher infant survival and reproductive success (Silk et al. 2003). Such social behaviour is linked to the biology of reward, since grooming stimulates the release of beta-endorphins in the monkey brain. This peptide is released in small-brained mammals during sex and parturition acting as a rewarding enforcer of behaviour, but in primates, this peptide has acquired the distinctive function of rewarding social encounters, thereby forming the "social glue" of these complex societies (Keverne et al. 1989). Indeed, the number of grooming relationships is one of the most powerful predictors of neocortex size in primates (Kudo and Dunbar 2001). Social behaviour has thus had a powerful impact on the evolutionary expansion of those cortical areas of the brain concerned with decision taking and reward, which is not surprising since many of these decisions are related to social reward.

In order for social reward to have gained such power in cortical expansion, it has been necessary for maternal care in particular to become emancipated from hormonal determinants. Indeed, unlike small brain rodents, maternal behaviour in monkeys is no longer closely tied into physiological homeostasis and the strong dependence on hormones. Post-partum rodents return to oestrous within 72 hours after removing their pups whereas female baboons have been seen to continue carrying and grooming their dead offspring for months after death. Moreover, older sisters and maternal relatives participate in offspring care without having undertaken pregnancy and parturition. Mothers themselves are thus not required to delay their next pregnancy until their

offspring are fully mature in brain development. Hence the advantage of the extended family network seen in Old World primates. Expansion of the neocortex releases maternal care from the restrictive confines of hormonal determinants, which benefits infant survival by further enabling non-parturient females to participate in offspring care and at the same time gain experience in mothering under the watchful eye of the matriarch.

Opioids and Primate Infant Attachment

The early development (first 10 weeks) of social behaviour in monkeys occurs primarily in the context of interactions with the mother. These early social interactions are almost totally under the mother's control, in terms of both the amount and kinds of interaction permitted with others in the group. By 40 weeks of age, infants are considerably more independent from their mother, and much of their behaviour is oriented towards peers. Nevertheless, mothers continue to monitor their infants and quickly intervene in response to risks arising during play (Simpson et al. 1989). The mother and her matriarch serve as a secure base from which the infant can obtain contact and grooming while developing and strengthening its social bonds with peers and other kin.

Administration of opioids has been shown to reduce the distress shown by infants of various species when separated from their mothers (Panksepp et al. 1997). For example, the opiate agonist morphine reduces distress vocalization rates in chicks, puppies, and rhesus monkeys. Processes involving opioid brain reward may therefore play a role in infant attachment, but to what extent is this the same mechanism that is deployed in development of social behaviour as well as in maternal bonding? This question has been investigated in a study of young rhesus monkeys given acute treatment with the opioid receptor blocker, naloxone, and observed in their natal group (Martel et al. 1995). Naloxone increases the duration of affiliative infant-mother contact and the amount of time the infants spend on the nipple. These effects occur even at one year of age, when the mothers are no longer lactating. Indeed, feeding is unaffected by naloxone treatment of infants, but play activity decreases and their distress vocalizations increase. Moreover, the opioid system in both infant and mother coordinates intimate contact during reunion (Kalin et al. 1995). These findings may be interpreted in terms of opiate receptor blockade reducing the "positive affect" that has accrued from the attachment relationship with mother and, as a result of which, the young infant returns to mother as the established secure base.

Opioids and Maternal Bonding

In addition to increasing OT synthesis in the brain, the hormones of pregnancy induce pro-opiomelanocortin synthesis, the precursor of the endogenous opioid, β-endorphin. It has been suggested that the activation of the endogenous opioid system at parturition and during suckling promotes the positive affect arising from maternal behaviour. In the early postpartum period, a mother's social interactions are almost exclusively with her infant, and opiate receptor blockade in the mother has marked effects on this relationship.

Studies on naloxone treatment of postpartum rhesus monkey mothers living in social groups have addressed the importance of opioids in maternal bonding. Naloxone treatment reduces the mothers' caregiving and protective behaviour shown towards their infants. In the first weeks of life, when infant retrieval is normally very high, naloxone-treated mothers neglect their infants and show little retrieval even when the infant moves a distance away. As the infants approach eight weeks of age, when a strong grooming relationship normally develops between mother and infant, mothers treated with naloxone fail to develop such a grooming relationship. Moreover, these mothers permit other females to groom their infants, whereas saline-treated controls are very possessive and protective of their infants (Martel et al. 1993).

The infant is not rejected from suckling, but the naloxone-treated mother's possessive preoccupation with the infant declines. She is not the normal attentive caregiver, and mother-infant interactions are invariably initiated by the infant. It is clear, therefore, that primates and other mammals have in common the involvement of endogenous opioids in maternal care, but the consequences of opioid blockade in small-brained mammals are much greater for the biological aspects of maternal behaviour. In rodents and sheep, interference with the endogenous opioid system severely impairs maternal behaviour, including suckling, whereas monkeys neglect their infant's social bonding but still permit suckling. These differences may reflect the degree of emancipation from endocrine determinants that maternal behaviour has undergone in Old World primates, and the importance of social reward activating the "bonding" mechanism.

Infant primates, both human and non-human, are highly susceptible to social perturbations in maternal care. The infant's developing brain requires social stimulation from a mother committed to providing the emotional rewards of suckling, huddling and grooming. It is clear that the process of infant socialization benefits from this close relationship and, because this occurs during early brain development, mother-infant separations are likely to have long-term consequences (Hinde et al. 1978). Indeed, in adults, extreme consequences for subsequent social relationships and maternal bonding occur if as infants they have been separated from their mothers and reared with peers (Suomi and Harlow 1975; Kraemer et al. 1991). Nursery-reared rhesus monkeys deprived of a maternal upbringing demonstrate reduced OT secretion and social behaviour but show increased aggressive and stereotypical behaviours. Increased stereotypical behaviours are often classically associated with the disruption of frontal cortical function and often result from an inability to suppress inappropriate behavioural responses (Winslow et al. 2003). Four years after experiencing separations from their mothers early during development, squirrel monkeys generate differences in emotional behaviour, stress physiology and development of the brain, notably in the medial prefrontal cortex (mPFC). Behavioural tests have subsequently shown these monkeys to be impaired in reward-related memory tasks (Lyons and Schatzberg 2003). Electrophysiological recordings from normal adult monkeys have shown the mPFC mediates the achievement of goals (Matsumoto and Tanaka 2004). The precise involvement of the prefrontal cortex in reward-related behaviour has also been examined in humans using imaging techniques (Fig. 3). Interestingly, the detection of unfavourable outcomes, response conflict and decision uncertainty elicit overlapping clusters of activation foci in the mPFC (Ridderinkhof et al. 2004). Choosing between actions associated with uncertain rewards and punishments in humans is mediated by neural circuitry involving frontal cortex, anterior cingulated and striatum (Rogers et al.

2004). Showing alternating videos of the own child versus that of a stranger to mothers provoked the greatest signal contrasts in the mPFC and orbito-frontal cortex. These distinctions required face recognition and emotional processing which correlated with activation in the visual cortex, temporal pole and amygdala (Ranote et al. 2004).

Discussion

The proximate determinants of mammalian social behaviour have their evolutionary origins in the mechanisms that subserve maternal care. Variations on this theme are exemplified across small-brained mammals, where the most important selective social bonds are seen between mother and offspring and between partners that mate. A great deal of attention has been given to "bonding" in the monogamous prairie vole, which has provided a tendency to focus on the peptides OT and vasopressin and the expression of their receptor genes as being evolutionarily conserved for "bonding." This mechanistic focus has been very important and influential but has not taken account of the broader aspects of biology that apply to small-brained mammals in general and parental care in particular. A comparison of mammalian maternal care and monogamous bonding reveals three common components of the biology that are

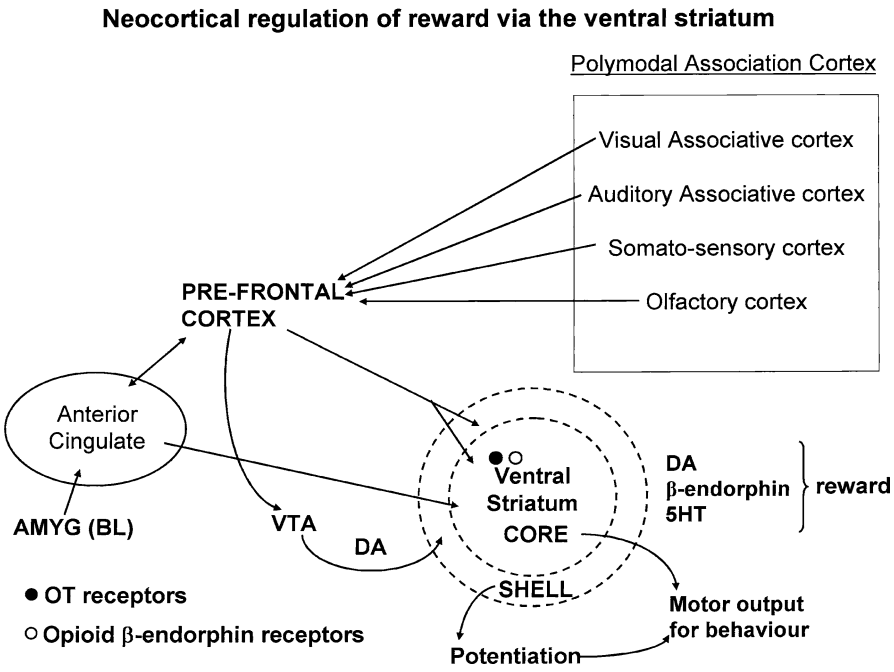

Fig. 3. The pre-frontal cortex dominates activation of the ventral striatum, processing a complexity of association cortical inputs in determining reward for motor output. Projections via the amygdala and anterior cingulate also provide pre-frontal cortex (medial pre-frontal) with emotional context

important: 1) hormonal priming by the foetal placenta for maternal care, cf. hormonal priming for oestrus by male pheromones in the vole; 2) vaginal-cervical stimulation at parturition, cf. vaginal-cervical stimulation at mating in the vole; and 3) olfactory recognition of offspring, cf. olfactory recognition of mating partner in the monogamous vole. Both maternal bonding and sexual bonding involve oxytocin in the female, a nine amino acid peptide that takes its evolutionary origins from vasotocin, which is also nine amino acids long. By the substitution of one amino acid, vasotocin has produced vasopressin, which in the male vole is required for "bonding," whereas the brain receptor distribution for both peptides has a focus on the nucleus accumbens and ventral pallidum. These neural structures form an integral part of the brain's social reward circuitry, which in small-brained mammals receives a primary input from olfactory circuitry.

Olfactory recognition is integral to sexual bonding in the monogamous prairie vole and integral to offspring recognition and maternal care in rodents as well as selective bonding in ungulates. Indeed, the selectivity of bonding through olfaction is extremely robust in ungulates, which forcibly reject all infants but their own with which they have bonded. The sexual bonding described for prairie voles is more akin to partner preference, since both males and females will and do mate with others given the opportunity. Monogamous pair bonding is also very rare among mammals (<5%), whereas maternal bonding applies to all mammals and, at a mechanistic level, probably formed the foundations from which all other social and bonded relationships, including monogamy, evolved.

Mammalian brain evolution recapitulated the reciprocal interplay between social bonding and maternal bonding. Evolutionary biologists hypothesise that increases in primate brain size have been driven by the selection pressures arising from living in social groups. Social living required an ability to predict how an individual's behaviour will impact differentially on other members of the group according to social status and how others, in turn, will react to this behaviour. However, since social cohesion and group continuity occurs through the matriline, field biologists often refer to the social group as being female bonded. To evolve brains as large as those seen in Old World primates and hominids, most of brain development has needed to be postponed to the post-natal period to facilitate the birth process. Such extensive periods of brain growth and maturation have required alloparental as well as maternal care, which has in turn required a degree of emancipation from the requirement for pregnancy hormones to determine maternal care. Maternal kin, including older sisters and aunts, can participate in offspring care and protection, thereby enhancing their own maternal skills, while the infant's brain is growing and maturing in a social environment, exposure to which will "imprint" important social skills. Equally important is provision of an attachment figure, primarily mother, which provides a secure base from which infants explore and develop other social relationships.

Understanding brain evolution is crucial to the realisation of what hormonal studies on small-brained mammals can and cannot inform us about primate, including hominid, brain and social behaviour. We already know from studies of animals with small brains that epigenetic processes are activated by the social environment. High levels of prosocial mothering (licking and grooming) produce offspring that also display the same prosocial behaviour, even if these offspring have been cross-fostered from a strain of mothers differing in a genetic background that produces low levels

of these behaviours. Extending primate brain development and maturation into an equally extensive post-natal social environment has introduced an additional period for such epigenetic modifications in determining the social functioning of the adult brain. Those epigenetic mechanisms that are activated by hormones, as part of physiological homeostasis, and shape the in-utero and early post-natal development of the brain, are but a first stage that is important to all mammals. The second stage, namely extensive post-natal development, is especially important to large- brained mammals, ensuring that the brain is exposed to a social environment that equips it to function well during a lifetime of social interactions.

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