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# Hormonal correlates of changes in interest in unrelated infants across the peripartum period in female baboons (*Papio hamadryas anubis* sp.)

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**Abstract**

In past research on human and nonhuman primates, maternal responsiveness and behavior has been thought of as an experiential, cognitive mechanism; however, recent findings have shown that maternal motivation and behavior may not be entirely divorced from the endocrine system. To investigate the relationship between interest in infants and the hormonal changes related to pregnancy, we examined the nature of social interactions across parturition between a large sample ($n$ = 133) of adult female baboons (*Papio hamadryas anubis* sp.) and unrelated infants. Prepartum data were collected during ten 30-min focal observations for each subject. Each mother–infant pair was then observed through the infant's first 8 weeks of life. A total of 2325 h of observation was recorded. Urine was collected on 65 subjects, starting 5 weeks before the expected date of parturition and ending 4 weeks after parturition. Evidence for a connection between endocrine function and responsiveness toward infants was found. Affiliative behaviors during the prepartum period were positively correlated to the estrogen/cortisol ratio and high dominance rank. In the postpartum period, affiliative behaviors were positively correlated with prepartum progesterone and dominance rank, and negatively correlated with postpartum cortisol levels. Finally, a positive correlation was recorded during the postpartum period between prepartum progesterone and aggression, and a negative correlation between postpartum cortisol and aggression and submission. Our data suggest that the endocrine changes that may help regulate maternal care of offspring also influence the way in which pre- and postpartum female baboons interact with unrelated infants in their social group.


*Keywords:* *Papio*; Baboon; Prepartum; Postpartum; Infant-directed behavior; Hormones; Urinary metabolites; Enzyme immunoassays

## Introduction

In nonprimate mammals, endocrine and neural changes represented during the peripartum period are critical to the onset of maternal motivation (Numan and Insel, 2003; Rosenblatt and Snowdon, 1996). Changes in endocrine levels, such as progesterone, estrogen, prolactin, and oxytocin, are important for pregnancy, parturition, maternal responsiveness, and lactation in most mammals (Pryce, 1996), and have been related to different maternal responses throughout the peripartum period.

The study of primate allomaternal behavior has most often focused on ultimate causes relevant to fitness and social organization rather than biological causes (Coe, 1990; Keverne, 1996; Lancaster, 1971; Pryce, 1992). Finding a connection between hormone levels and expressed maternal responsiveness in primates is complicated by species differences in hormone profiles evident in pregnant and lactating females (marmoset, French et al., 1996; baboon, Albrecht and Townsley, 1978; Fortman et al., 1993; human, Fleming et al., 1995), the tremendous variability in maternal care patterns both within and between species (Rosenblatt,

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2002), and the different methodology used to measure endocrine hormones.

A number of studies on human and nonhuman primates have suggested that hormones can account, at least in part, for the individual variability and changes in maternal motivation during the pre- and postpartum period. However, some discrepant findings, together with the complexity of the social system and infant development, make them difficult to generalize. Pryce et al. (1988) found that elevated urinary estradiol levels during the prepartum period in primiparous tamarin (*Saguinus labiatus*) females were associated with the rate of infant survival during the postpartum period. An experiential study on marmosets (*Callithrix jacchus*) supported this view, reporting that primiparous females treated with progesterone and estradiol to mimic late pregnancy steroid profiles showed increased maternal motivation (Pryce, 1993). However, later studies did not report a significant relationship between estradiol, progestin, and behavioral measures (Pryce et al., 1995). A study of black tufted-ear marmoset (*Callithrix kuhlii*) females found the opposite relationship: increased estradiol levels during the prepartum period were found to be correlated with high infant mortality rates as an effect of poor maternal care during the postpartum period (Fite and French, 2000).

Evidence of a connection between the physiological state of the female and maternal responsiveness has also been reported in Old World monkeys and apes, however contradictory results also exist. Bahr (1995) reported that female gorillas (*Gorilla gorilla*) with high levels of progesterone scored the highest in maternal competence, but a later expansion of the study did not support a relationship between hormone levels and behavior (Bahr et al., 2001). In ovariectomized female rhesus macaques (*Macaca mulatta*), exogenous administration of estradiol increased the rate of interaction with unrelated infants (Maestripieri and Zehr, 1998). In pigtail macaques (*Macaca nemestrina*), pregnant females' interest in infants was related to reproductive status (Maestripieri and Wallen, 1995), and some aspects of social behavior changed in association with sex steroid fluctuations during pregnancy (Maestripieri, 1999). In Japanese macaques (*Macaca fuscata*), mothers characterized by a rejecting maternal style showed significantly lower levels of excreted estrogen conjugates ($E_1C$) in late pregnancy (Bardi et al., 2001a), changes in social behavior were correlated with $E_1C$ fluctuations during the peripartum period (Bardi et al., 2001b), and maternal responsiveness was related to changing levels of estrogen and cortisol during the late prepartum and early postpartum period (Bardi et al., 2003). Recent findings have also shown that baboon (*Papio hamadryas anubis*) mothers with higher prepartum cortisol levels tended to display higher levels of affiliative infant-directed behaviors (Bardi et al., 2004).

In humans, mothers with higher levels of cortisol displayed more nurturing behavior toward their infants (Fleming et al., 1995). Fleming et al. also reported that the pattern of change in the ratio of estradiol to progesterone during pregnancy was related to the mother's reported feelings of attachment for the infant (Fleming et al., 1997a). Salivary cortisol was positively correlated with levels of affectionate contact in primiparous women, but not in multiparous females (Fleming et al., 1997b).

While some inconsistencies exist within the literature, primate studies provide accumulating evidence that sex steroid hormones and the HPA activity are associated with maternal behavior, a relationship moderated by experience, social organization, genetic factors, and other elements of the environment. This study was design to better address the complexity of primate maternal responsiveness, taken into consideration maternal characteristics, physiological activity, and social dynamics in a large sample size within a controlled environment.

The purpose of this study was to examine the nature of social interactions between a large sample of adult female baboons (*P. hamadryas anubis*) and unrelated infants (from birth to 1.4 years of age) through the third trimester of pregnancy and the 8 weeks following the birth of the infant. We considered the dominance rank of the female and the reciprocal nature of social interactions to better characterize the relationship. The present study took into account the bidirectional nature of social interactions between the female and unrelated infant, the dominance rank of the female, which has been known to influence social interactions, and correlated these social attributes with physiological mechanisms. We specifically tested the hypotheses that the frequency of females' interaction with unrelated infants would increase from the prepartum to postpartum period, reflecting major changes within their physiological and reproductive state as measured in hormone levels (Bardi et al., 2001b; Maestripieri, 1999). We also tested the hypothesis that behavioral modifications were coordinated by changes in steroid hormone levels during the perinatal period as measured by an increase in maternal interest toward infants (Bardi et al., 2003; Maestripieri and Zehr, 1998).

## Methods

### *Subjects and study site*

The study took place at the Southwest Foundation for Biomedical Research, San Antonio, TX. We studied 133 female olive baboons (*P. hamadryas anubis* sp.) living in single-male social groups with approximately 30 other adult females and their offspring. Subjects were between the ages of 5.7 and 19 years and were identified by numbered tags worn around their necks. Each group had an average of 5.16 infants ranging in age from newborn to 1.4 years (mean 0.58 years). Each female in the social group belongs to different matrilines and infants were weaned and moved to peer groups at about 1 year of age. Thus, social interactions were unlikely to be biased by kin selection and more likely to reflect individual attraction to infants. All subjects lived in identical 47-$m^2$ enclosures, with climbing structures and heated indoor dens. Caretakers fed the animals and cleaned their cages on the same schedule.

The use of subjects adhered to the Guide for the Care and Use of Laboratory Animals (National Research Council, 1996) and was approved by the Institutional Animal Care and Use Committee (animal welfare assurance # A3082-01, approved on April 24, 2001).

*Behavioral data collection*

The estimated date of pregnancy was determined by the pattern and color of the sex skin swelling, a reliable visual indicator of reproductive status in the baboon (Hendrickx, 1965). During the last 8 weeks of the prepartum period, data were collected during ten 30-min focal observations for each female subject. The frequency of all social interactions (see Table 1) was recorded on paper, including those interactions with unrelated infants in the cage. After the date of parturition, each mother–infant pair was then observed through the infant's first 8 weeks of life by conducting between forty-eight and sixty 15-min focal observations to gauge behavioral interactions between the mother–infant pair and all other individuals within the enclosure. For the postpartum period, mother–infant data were collected using the Observer® data collection program on a portable laptop computer.

Dominance matrices to determine the female's rank were constructed using the prepartum data by considering the directionality of affiliative, submissive, and aggressive behaviors given and received by the subject to all other adult individuals within the social group. This analysis did not include any social interactions with infants. Social rank was further determined by the subject's priority of access to a preferred food source (fruit), which was placed at the front of the cage by the observer who then recorded the order of approaching females. Each individual in each social group was then ranked on a scale of high, medium, and low rank by evaluating the dominance matrices and food access.

The observational data collected on each subject were summarized to determine the frequency and type of social interactions grouped into categories of affiliative, aggressive, and submissive behaviors directed toward and received by unrelated infants within the social group during the prepartum and postpartum period, starting 8 weeks before delivery and ending 8 weeks after delivery. A total of 2325 h of observations was recorded.

To determine the trends in social interactions with unrelated infants across the perinatal period, the number of days before and after parturition was determined for each behavioral observation. Graphs were constructed for the mean frequency of each category of social interaction over the pre- and postpartum period.

Because the availability of unrelated infants in the group could influence the frequency of social interactions, we corrected the data for the number of infants in each social group by calculating the number of unrelated infants for each subject. The mean number of infants in the group during all the prepartum observations and the number of infants at two time points in the postpartum periods (not including the subject's own infant) were calculated by reviewing the animal records database. We divided the original frequency of social interactions by the mean number of infants present in any of the time periods. We chose to weigh the social behaviors using the mean number of infants because we found a linear correlation between the number of unrelated infants and the frequency of social interactions in the behavior categories.

*Hormone assays*

Urine was collected from a subset of 65 of the subjects. Urine samples were collected from each baboon starting 5 weeks before the expected date of parturition and ending 4 weeks after parturition. Accordingly, urine samples do not

Table 1
Social behaviors analyzed and used in summarization

| Category | Individual behaviors recorded |
|---|---|
| Affiliative | Approach, attempt to hold, attempt to touch, cling, embrace, enlist to aid, enlist to groom, enlist to play, follow, groom, huddle or hold, ignore, inspect (exploration of anogenital area), jump or climb on, lick, lipsmack (rapid movement of lips), mouth genitals, muzzle (placing the muzzle within 6 in. of the muzzle of a recipient), olfactory, oral (chewing, mouthing, biting, licking, or sucking on another), play (grapple, mouth, chase), receive jump on, touch (extension of any limb to make contact with another), touch genitals |
| Submissive | Attempt to flee, avoid, ear flatten (depression of the ears against the side of the head), flee, grimace (pulling back lips to expose teeth), head bob (repetitive up and down movement of the head directed toward another), present, rapid glances (a nervous, repetitive pivoting of the head in attempt to avoid eye contact with another) |
| Aggressive | Bite (closing the teeth on another animal's body), brow raise (facial expression in which the lightened skin above the eyes becomes visible), chase, displace (supplanting another animal and occupying that space), display, fight ("wrestling" between two or more individuals), grab, hit, hit at, joust (bobbing from side to side facing another individual), jump on, lung (rapid transference of weight to forelimbs while keeping hind limbs stationary), open mouth, piloerection, pull, pull hair, push, rough handling (careless manipulation of infant), round mouth, rub or slap ground, stare (fixed gaze toward another accompanied by a tense, rigid posture of the upper anatomy), take object, teeth gnash (audible grinding of teeth) |

exactly parallel the time frame of behavioral data collection. Samples were collected twice per week for each, between 0700 and 0900 h (total of 1170 samples). Subjects were moved from their home enclosure via a transfer chute to a separator area. Urine was collected from an aluminum pan, which was placed under each separate cage. Upon urinating, females were rewarded with fruit and returned to their social group.

Enzyme immunoassays (EIAs) were used to measure levels of excreted gonadal and adrenal steroids, including cortisol, pregnanediol-3-glucoronide (PdG), and various estrogen conjugates ($E_1C$). Assay validation and details on the procedure have been reported elsewhere (French et al., 1996). Validation procedures have shown that urine measures of steroid hormones in baboons were highly correlated with serum samples (French et al., 2004). Microtiter plates (Nunc-Immuno MaxiSorp F96) were coated with 50 μl of antibody raised against a steroid-bovine albumin antigen in rabbit and diluted to the appropriate concentration in EIA phosphate buffer (0.1 M sodium phosphate, containing 0.087 NaCl and 0.1% bovine serum albumin). Coated plates were sealed, incubated for 1–2 days, and washed before removing antibody not covalently bounded to the plate well. EIA buffer was added to each well, along with duplicate aliquots of reference standard (Sigma), quality control samples, and urine samples. Steroid-HRP conjugate was added to wells and the plates were incubated for 2 h. After incubation, the plates were washed to separate unbound from bound hormone. Substrate solution (ABTS-$H_2O_2$) was added immediately, and absorbance was measured at 410 nm (reference 570 nm) with a Dynatech MR5000 Microtiter Plate Reader. A four-parameter sigmoid-fit curve was used to calculate sample concentrations.

Aliquots taken from a pool of pregnant baboon urine were assayed on each plate to monitor assay quality control. The intra-assay coefficients of variation were 3.3%, 3.7%, and 9.6% for cortisol, PdG, and $E_1C$, respectively. Inter-assay CV's were 6.2%, 7.5%, and 17.5% for cortisol, PdG, and $E_1C$, respectively. To control for variation in fluid intake and output by baboons, hormone concentrations were corrected for the creatinine content of each sample using a modified Jaffé end-point reaction assay (described in French et al., 1996).

### *Statistical analysis*

Statistical analyses were performed to assess significant changes in responsiveness to unrelated infants across the pre- and postpartum period. To account for the small number of observations or missing data for some subjects during particular weeks, all social interactions by the subjects and the unrelated infants were collapsed into three periods: 8 weeks prepartum, the first 4 weeks postpartum, and the last 4 weeks postpartum. Twenty-two females did not have adequate postpartum data due to illness, injury, or infant removal, thus 111 females were used in this statistical analysis. We analyzed the temporal variation of four behavioral categories using an ANOVA with repeated measures, with three periods (prepartum, postpartum 1–4, and postpartum 5–8) as the temporal factor (time) and dominance as the categorical factor (rank). The behavioral categories were affiliative performed and received, aggression performed, and submission performed. The frequencies of aggression and submission received were too low to be analyzed statistically. When a significant difference over time was found, we used the Fisher LSD post hoc tests to reveal which period was responsible for the overall significance. Moreover, because four tests were made on the same 68 subjects for behavioral variables that were also partly correlated, we used the Bonferroni procedure to adjust the alpha values to avoid an inflated risk of type I error (Hays, 1991). The type I error rate per comparison ($\alpha$pc) was set to $\alpha = 0.012$ for significance and $\alpha = 0.002$ for high significance. In the text, conventional $P$ values are reported with significance and marked with an asterisk (*), and respectively high significance marked with a double asterisk (**).

Multiple regression analysis was used to assess the effects of hormones and rank on social interactions toward unrelated infants. A stepwise forward approach was selected to include the categorical variable rank as a dummy variable. Dummy variables have the advantage over multicategory nominal variables of being subject to meaningful mathematical manipulation. While a multi-category nominal variable cannot be used in its original form as a predictor in regression analysis, the dummy variables formed from this nominal variable can be used (Diekhoff, 1992). Therefore, the following variables were entered in the model one at a time: pre- and postpartum $E_1C$, PdG, and cortisol; the prepartum $E_1C$/PdG ratio; the $E_1C$/cortisol ratio (prepartum $E_1C$ and postpartum cortisol levels); and low, middle, and high social rank. On the first step of the analysis, the predictor explaining the greatest part of variance was included in the equation. On the second step, a second predictor was included that added the most additional explained variables. At each step, the predictor that provided the greatest increase in $R^2$ was added. The inclusion of additional predictors was halted when the inclusion failed to provide a significant increase in $R^2$.

Data analysis was carried out using the package Statistica (Statsoft Inc., 1998).

## Results

### *Peripartum changes in behavior*

Visual inspection of the frequency of interactions between the 133 subjects and unrelated infants showed that females exhibited an overall increase in the weekly frequency per hour of all social interactions (affiliative, aggressive, and submissive), with the exception of the week before the date of parturition (Fig. 1).

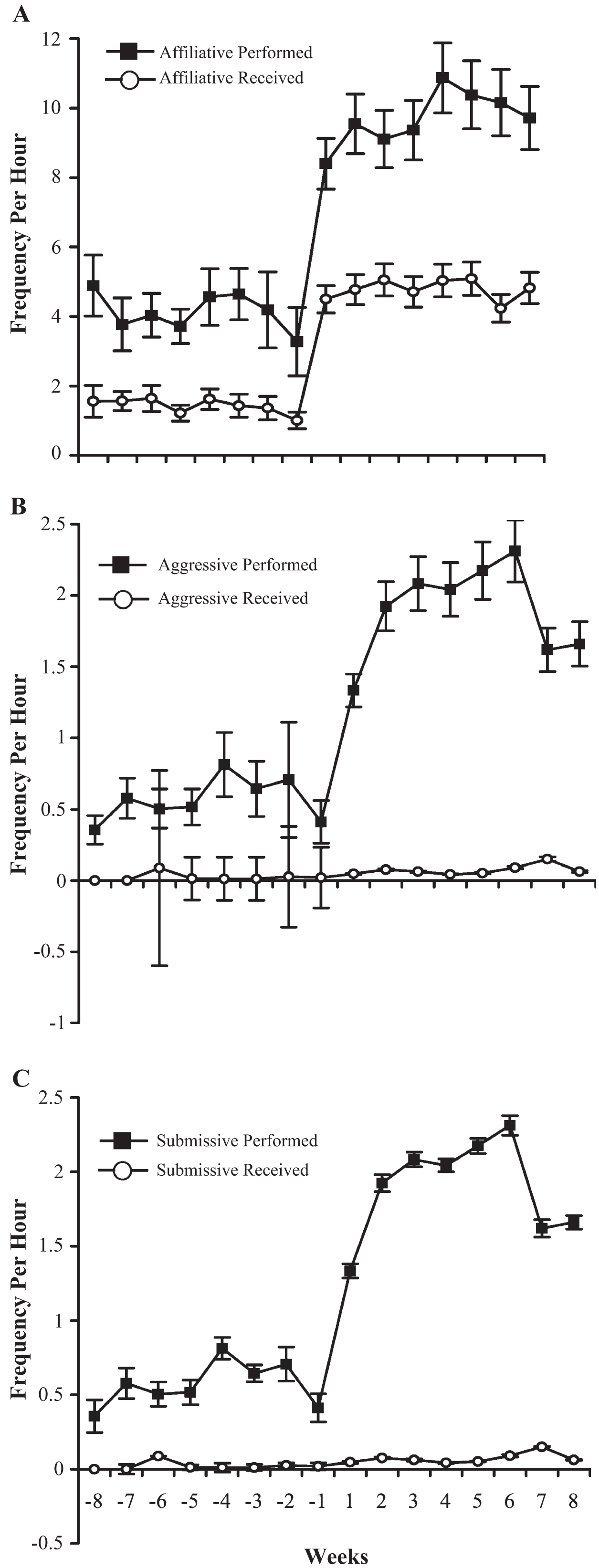


Fig. 1. Trends of interactions with unrelated infants in female baboons during the last 8 weeks of the prepartum period through the first 8 weeks of the postpartum period. Weekly trends of (A) affiliative and receive affiliative behaviors, (B) aggressive and receive aggressive behaviors, and (C) submissive and receive submissive behaviors, in frequency per hour (mean ± SEM, $N$ = 133). Values seen in weekly trends are calculated by the number of observations and are not modified for the number of infants within each observation period.

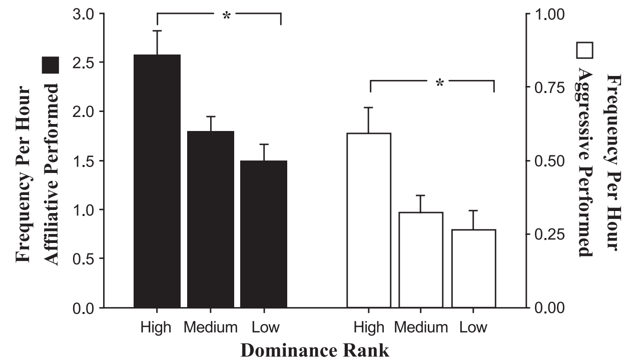


Fig. 2. Variation in affiliative and aggressive behaviors performed related to dominance rank of pregnant females during the peripartum period in olive baboons. High-ranking females displayed significantly more affiliative and aggressive behaviors toward unrelated infants than low-ranking females. Values are expressed as mean (±SEM), $N$ = 111.

We found that dominance was significantly related to the overall levels of aggressive behavior (rank: $F_{2,108}$ = 4.832; $P < 0.009$*) and affiliative behavior (rank: $F_{2,108}$ = 6.891; $P < 0.0015$**) (Fig. 2). Fisher post hoc tests showed that high-ranking females displayed significantly higher rates of aggressive behavior and affiliative behavior toward unrelated infants than low-ranking females ($P < 0.001$**).

Analyses revealed a significant increase in aggression displayed toward unrelated infants from the prepartum to the postpartum period (time: $F_{2,216}$ = 15.218; $P < 0.001$**). We also found that the subjects' affiliative social interactions, both directed toward (time: $F_{2,216}$ = 49.113; $P < 0.001$**) and received by (time: $F_{2,216}$ = 33.039; $P < 0.001$**) unrelated infants significantly increased from the prepartum to postpartum period (Fig. 3).

There was no significant interaction between time and rank for either aggressive behavior (time × rank: $F_{4,216}$ = 1.260; NS) or affiliative behavior displayed by the subjects (time × rank: $F_{4,216}$ = 2.046; NS). Furthermore, the rate of submissive behavior toward unrelated infants was not significantly affected by rank, time, or the interaction effect of time and rank.

### *Correlations of hormones and behavior*

Both estrogen and progesterone metabolites dropped to very low values right after parturition (Fig. 4). A state of mild hypercortisolism during the prepartum period was followed by a small but significant decrease after parturition

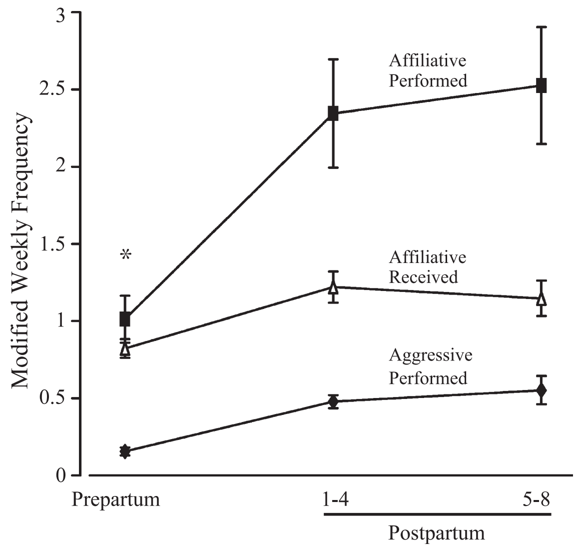


Fig. 3. Variation in changes over time from the prepartum period through the postpartum period weeks 1–4 and postpartum period weeks 5–8 of affiliative performed, affiliative received, and aggressive behaviors performed in female baboons. Values represent weekly mean frequencies of social interactions with infants divided by the mean number of infants (mean ± SEM, $N = 111$). Both postpartum 1–4 and 5–8 were significantly higher than the prepartum values.

($t$ test for dependent samples = 5.1, $P < 0.001$). Univariate correlation among the six dependent variables (peripartum behaviors) and the 11 independent variables (hormonal values and ranks) indicated a positive association between prepartum affiliative behavior and both prepartum $E_1C$ ($r$ = 0.26) and the $E_1C$/cortisol ratio ($r$ = 0.28). Moreover, postpartum affiliative ($r$ = 0.31) and aggressive ($r$ = 0.41) behaviors were significantly related to prepartum PdG levels.

Social behaviors received by the mother from the infant were too low to be included in the regression models and as a result the remaining results will focus on behaviors directed toward the unrelated infant. Multiple regression analyses revealed that prepartum affiliative behaviors directed toward unrelated infants were significantly related to the $E_1C$/cortisol ratio (partial correlation: $r$ = 0.27) and to high dominance rank (partial correlation: $r$ = 0.14) ($R$ = 0.31; $F_{2,60}$ = 3.2; $P < 0.05$). Affiliative behaviors directed toward unrelated infants during the postpartum period were related to prepartum PdG (partial correlation: $r$ = 0.35), postpartum cortisol (partial correlation: $r = -0.19$), the prepartum $E_1C$/PdG ratio (partial correlation: $r$ = 0.16), and high dominance rank (partial correlation: $r$ = 0.16) ($R$ = 0.43; $F_{4,58}$ = 3.3; $P < 0.05$).

Prepartum aggression directed toward unrelated infants was not related to hormonal levels during the peripar-tumperiod ($R$ = 0.27; $F_{2,60}$ = 2.4; NS). Postpartum aggression directed toward unrelated infants was related to the average prepartum PdG levels (partial correlation: $r$ = 0.36), the average postpartum cortisol levels (partial correlation: $r = -0.15$), and low dominance rank (partial correlation: $r = -0.15$). The model including these three variables was significant ($R$ = 0.46; $F_{3,59}$ = 5.4; $P < 0.01$).

Prepartum submission was not related to the physiological status of females (prepartum submission: $R$ = 0.24,

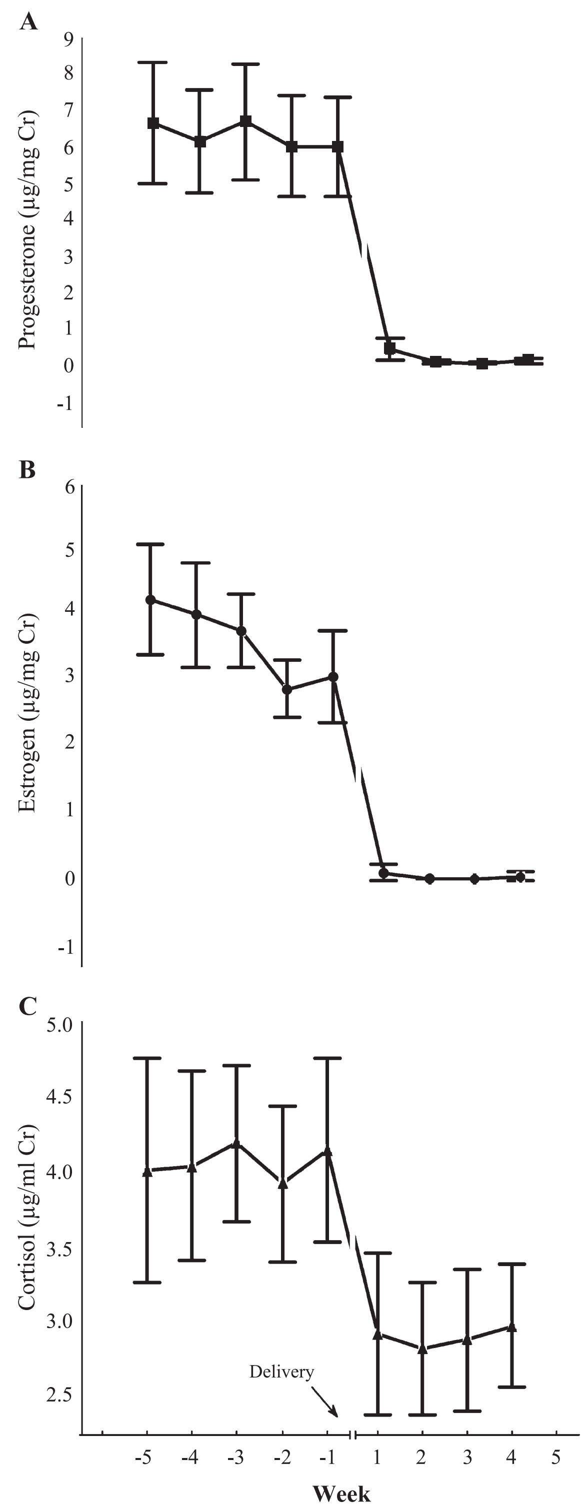


Fig. 4. Variation in excreted progesterone (A), estrogen (B), and cortisol (C) levels over time from 4 weeks before parturition to 5 weeks after birth in pregnant female baboons. Values are expressed as mean (±SEM), $N = 65$.

$F_{3,59}$ = 1.2, NS). Finally, postpartum submission was significantly related to postpartum cortisol (partial correlation: $r = -0.22$) ($R = 0.35$; $F_{3,59} = 2.8$; $P < 0.05$) and low dominance rank (partial correlation: $r = 0.39$).

## Discussion

In this study, utilizing a large number of subjects, we found evidence for a connection between reproductive status, social status, endocrine function, and responsiveness toward unrelated infants in female baboons. Specifically, social interactions with unrelated infants varied in relation to the time period, the type of interaction, the subject's rank, and peripartum hormonal changes.

Social interactions of females with unrelated infants increased significantly from the late prepartum to the early postpartum period, as has been found in other nonhuman primates (Coe, 1990; Maestripieri and Wallen, 1995; Maestripieri and Zehr, 1998). In addition, interactions with infants decreased during the last week of the prepartum period. This may be due in part to the mother isolating herself from the social group in preparation of the delivery of the infant, as has been found in previous studies (Bardi et al., 2001b; Maestripieri, 1999; Martel et al., 1994; Nieuwenhuijsen et al., 1986; Silk, 1987). Altmann (1987) reported that female baboons in Kenya are at their highest predation risk during pregnancy and lactation due to their decrease in social involvement.

Our data indicate that the trends in responsiveness toward infants were also related to the subjects' rank and hormone concentrations. High-ranking females were more socially active than low-ranking females during the whole peripartum period. It has been hypothesized that low-ranking females should actively try to exploit the higher attractiveness involved in carrying a newborn to interact with high-ranking females and their offspring (Maestripieri, 1994; Seyfarth, 1980). However, our results do not indicate an interaction between rank and social interactions with infants across parturition.

Peripheral endocrine profiles in female baboons during the last trimester of pregnancy and especially across parturition vary dramatically, thus repeated sampling is crucial (Albrecht and Pepe, 1990; Albrecht et al., 1989; Nguyen et al., 1999). However, invasive methodology that is required for frequent blood sampling could potentially alter the nature of the mother–infant bond, as well as activating the hypothalamic–pituitary–adrenal axis. As a result, we collected repeated samples using noninvasive methodologies for biological substrates other than plasma in efforts to reduce this problem (Whitten et al., 1998). We found that affiliative behaviors during the prepartum period were positively correlated to the $E_1C$/cortisol ratio and high dominance rank. In the only previous study assessing this ratio in any primate species, a positive association with maternal responsiveness has been found in Japanese macaques, indicating that the reciprocal action of adrenal and gonadal axes could directly affect mothers' interest in infants (Bardi et al., 2003).

Affiliative behaviors were also related to the level of $E_1C$ in the univariate correlation, but the regression model we provided indicates that $E_1C$ values in relation to cortisol activity represent a better indicator of the mothers' interest toward infants. Indeed, adrenocortical activity is related to changes in sex steroid hormones occurring during the last phase of pregnancy, a condition attributed to an estrogen-stimulated increase in cortisol-binding globulin and placental production of corticotropin-releasing hormone (CRH) (McLean and Smith, 1999). Moreover, in the only study on nonhuman primates that tested this index, a significant association with maternal responsiveness was found (Bardi et al., 2003). Therefore, it is not surprising that the $E_1C$/cortisol ratio represents a good indicator of the interest in unrelated infants. No significant association was found between hormones measured and aggressive and submissive behaviors displayed toward unrelated infants during the prepartum period.

During the postpartum period, we found that affiliative behaviors were positively correlated with prepartum PdG, the sex steroid $E_1C$/PdG ratio, and dominance rank, while they were negatively correlated with postpartum cortisol levels. The sex steroid hormones progesterone and estrogen, and the adrenal glucocorticoid cortisol, have been associated to some degree with maternal behavior in several primate species (tamarins, Pryce et al., 1993; macaques, Bardi et al., 2001a; Maestripieri, 1999; gorillas, Bahr et al., 1998; baboons, Bardi et al., 2004). Maternal responsiveness was also increased experimentally through exogenous administration of estradiol alone (Maestripieri and Zehr, 1998) or in combination with progesterone (Pryce et al., 1993).

These hormones may mediate maternal attentiveness toward infants via a double feedback loop: high $E_1C$/PdG values could enhance maternal motivation, whereas high postpartum cortisol levels could inhibit maternal motivation (Pryce, 1996). The independent, additive positive effects of PdG could be explained by the ability of sex steroid hormones to alter the function of the serotonin neural system (Bethea et al., 2002), because during the peripartum period there is a clear connection between estrogens and progesterone. Estrogen regulates the receptor-mediated uptake of low density lipoprotein-cholesterol (LDL) that, in turn, promotes the production of progesterone (Albrecht, 1980; Henson et al., 1992). Additionally, estrogen acts on the fetal adrenal gland to modulate the production of androgen precursors, which ensure maintenance of physiologic levels of estrogen during the prepartum period (Challis et al., 2000). Furthermore, estrogen plays a role in the regulation of placental corticosterone metabolism and their secretion into fetal circulation, hence affecting the fetal hypothalamic–pituitary–adrenocortical axis (McLean and Smith, 1999; Pepe et al., 1990). The progesterone impact on the function of the serotonin neural system at both the afferent and efferent circuits can explain the impact of sex hormones on mood, cognition, and anxiety, thus modulating maternal motivation and, in the end, maternal behavior (Bardi et al., 2004). The associations between endocrine measures and postpartum aggressive and submissive behaviors displayed toward unrelated infants reflect those for affiliative behavior.

It is important to emphasize the close relationship between both pre- and postpartum physiologically mediated effects and the social status of females. High-ranking females interact more often with unrelated infants than middle and low-ranking females, independently of their physiological status, illustrating important contributions of both neuroendocrine changes and the social environment (Cacioppo and Bernston, 2002).

Our results show that the hormonal and social status of the mother is significantly related to her interaction level with unrelated infants. Nevertheless, other proximate factors cannot be overlooked. The new baboon mother is often the center of attention, and interactions that the female receives from others increase greatly after the birth of an infant (Altmann, 1980). We found that unrelated infants also significantly increased interactions with the postpartum subjects. Given the bidirectional nature of social interactions, the subject may have been responding to the unrelated infants in a reciprocal manner, thus indicating another possible variable influencing maternal responsiveness across the perinatal period.

The involvement of the endocrine system in the regulation of maternal responsiveness can be viewed as an adaptive strategy in an evolutionary framework, enabling the neurobehavioral modifications necessary for females to care for their infants (Numan and Insel, 2003). Our approach, using a multilevel integrative analysis including both neuroendocrine and social behavioral data, is beneficial when trying to understand the causes of highly complex activities such as maternal behavior (Becker et al., 2002). The complexity of interactions among the many components of the behavioral, endocrine, and social systems points toward a variety of positive and negative feedback loops supporting the physiological basis for increased responsiveness toward infants.

## Uncited references

Liu et al., 1997
Weaver et al., 2002

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## References

Albrecht, E.D., 1980. A role for estrogen in progesterone production during baboon pregnancy. Am. J. Obstet. Gynecol. 136, 569–574.

Albrecht, E.D., Pepe, G.J., 1990. Placental steroid hormone biosynthesis in primate pregnancy. Endocr. Rev. 11, 124–150.

Albrecht, E.D., Townsley, J.D., 1978. Serum estradiol in mid and late gestation and estradiol/progesterone ration in baboons near parturition. Biol. Reprod. 18, 247–250.

Albrecht, E.D., Crenshaw, MC., Pepe, G.J., 1989. The effect of estrogen on placental delivery after fetectomy in baboons. Am. J. Obstet. Gynecol. 160, 237–241.

Altmann, J., 1980. Baboon Mothers and Infants. Harvard Univ. Press, Cambridge, MA.

Altmann, J., 1987. Life span aspects of reproduction and parental care in anthropoid primates. In: Lancaster, J.B., Altmann, J., Ross, A.S., Sherrod, L.R. (Eds.), Parenting Across the Life Span. Aldine, New York, pp. 15–26.

Bahr, N.I., 1995. Environmental factors and hormones: their significance for maternal behavior in captive gorillas. In: Pryce, C.R., Martin, R.D., Skuse, D. (Eds.), Motherhood in Human and Nonhuman Primates, Schultz-Biergert Symposium, 3rd Kartause Itingen. Karger, Basel, pp. 94–105.

Bahr, N.I., Pryce, C.R., Dobeli, M., Martin, R.D., 1998. Evidence from urinary cortisol that maternal behavior is related to stress in gorillas. Physiol. Behav. 64, 429–437.

Bahr, N.I., Martin, R.D., Pryce, C.R., 2001. Peripartum sex steroid profiles and endocrine correlates of postpartum maternal behavior in captive gorillas (*Gorilla gorilla gorilla*). Horm. Behav. 40, 533–541.

Bardi, M., Shimizu, K., Fujita, S., Borgognini-Tarli, S., Huffman, M.A., 2001a. Hormonal correlates of maternal style in captive macaques (*Macaca fuscata* and *M. mulatta*). Int. J. Primatol. 22, 647–662.

Bardi, M., Shimizu, K., Fujita, S., Borgognini-Tarli, S., Huffman, M.A., 2001b. Social behavior and hormonal correlates during the perinatal period in Japanese macaques. Horm. Behav. 39, 239–246.

Bardi, M., Shimizu, K., Barrett, G.M., Borgognini-Tarli, S.M., Huffman, M.A., 2003. Peripartum cortisol levels and mother–infant interactions in Japanese macaques. Am. J. Phys. Anthropol. 120, 298–304.

Bardi, M., French, J.A., Ramirez, S.M., Brent, L., 2004. The role of the endocrine system in baboon maternal behavior. Biol. Psychiatry 55, 724–732.

Becker, J.B., Breedlove, S.M., Crews, D., McCarthy, M.M. (Eds.), Behavioral Endocrinology. MIT Press, Cambridge, MA.

Bethea, C.L., Mirkes, S.J., Su, A., Michelson, D., 2002. Effects of oral estrogen, raloxifene and arzoxifene on gene expression in serotonin neurons of macaques. Psychoneuroendocrinology 27, 431–445.

Cacioppo, J.T., Bernston, G.G., 2002. Social neuroscience. In: Cacioppo, J.T., Bernston, G.G., Taylor, S.E., Schacter, D.L. (Eds.), Foundations in Social Neuroscience. MIT Press, Cambridge, MA, pp. 1–10.

Challis, J.R.G., Matthews, S.G., Gibb, W., Lye, S.J., 2000. Endocrine and paracrine regulation of birth at term and preterm. Endocr. Rev. 21, 514–550.

Coe, C.L., 1990. Psychobiology of maternal behavior in non-human primates. In: Kransegor, N.A., Bridges, R.S. (Eds.), Mammalian Parenting. Oxford Univ. Press, Oxford, UK, pp. 157–183.

Diekhoff, G., 1992. Statistics for the Social and Behavioral Sciences. Wm. C. Brown, Dubuque, IA.

Fite, J.E., French, J.A., 2000. Pre- and postpartum sex steroids in female marmosets (*Callithrix kuhlii*): is there a link with infant survivorship and maternal behavior? Horm. Behav. 38, 1–12.

Fleming, A.S., Corter, C., Steiner, M., 1995. Sensory and hormonal control of maternal behavior in rat and human mothers. In: Pryce, C.R., Martin, R.D., Skuse, D. (Eds.), Motherhood in Human and Nonhuman Primates, Schultz-Biergert Symposium, 3rd, Kartause Ittingen. Karger, Basel, pp. 106–114.

Fleming, A.S., Ruble, D., Krieger, H., Wong, P.Y., 1997a. Hormonal and experiential correlates of maternal responsiveness during pregnancy and the puerperium in human mothers. Horm. Behav. 31, 145–158.

Fleming, A.S., Steiner, M., Corter, C., 1997b. Cortisol, hedonics, and maternal responsiveness in human mothers. Horm. Behav. 32, 85–98.

Fortman, J.D., Herring, J.M., Miller, J.B., Hess, D.L., Verhage, H.G., Fazleabes, A.T., 1993. Chorionic gonadatropin, estradiol, and progesterone levels in baboons (*Papio anubis*) during early pregnancy and spontaneous abortion. Biol. Reprod. 49, 737–742.

French, J.A., Brewer, K.J., Shaffner, C.M., Schalley, J., Hightower-Merritt, D.L., et al., 1996. Urinary steroid and gonadotropin excretion across the reproductive cycle in females Wied's black tufted-ear marmosets (*Callithrix kuhili*). Am. J. Primatol. 40, 231–245.

French, J.A., Koban, T., Rukstalis, M., Ramirez, S.M., Bardi, M., Brent, L., 2004. Excetion of urinary steroids in pre- and postpartum female baboons (*Papio hamadryas anubis* sp.). Gen. Comp. Endocrinol. 137, 69–77.

Hays, W.L., 1991. Statistics. Harcourt Brace, Orlando.

Hendrickx, A.G., 1965. The menstrual cycle of the baboon as determined by the vaginal smear, vaginal biopsy, and perineal swelling. In: Vagtborg, H. (Ed.). The Baboon in Medical Research vol. II. University of Texas Press, Austin, TX, pp. 70–83.

Henson, M.C., Pepe, G.J., Albrecht, E.D., 1992. Developmental increase in placental low density lipoprotein uptake during baboon pregnancy. Endocrinology 130, 1698–1706.

Keverne, E.B., 1996. Psychopharmacology of maternal behavior. J. Psychopharmacol. 10, 16–22.

Lancaster, J., 1971. Play-mothering: the relations between juvenile females and young infants among free-ranging vervet monkeys (*Cercopithecus aethiops*). Folia Primatol. 15, 161–182.

Liu, E., Diorio, J., Tannenbaum, B., Caldji, C., Francis, D., Freedman, A., Sharma, S., Pearson, D., Plotsky, P.M., Meaney, M.J., 1997. Maternal care, hippocampal glucocorticoid receptors, and hypothalamic–pituitary–adrenal responses to stress. Science 27, 1659–1662.

Maestripieri, D., 1994. Social structure, infant handling, and mothering styles in group-living Old World monkeys. Int. J. Primatol. 15, 531–553.

Maestripieri, D., 1999. Changes in social behavior and their hormonal correlates during pregnancy in pig-tail macaques. Int. J. Primatol. 20, 707–718.

Maestripieri, D., Wallen, K., 1995. Interest in infants varies with reproductive condition in group-living female pigtail macaques (*Macaca nemestrina*). Physiol. Behav. 57, 353–358.

Maestripieri, D., Zehr, J.L., 1998. Maternal responsiveness increases during pregnancy and after estrogen treatment in macaques. Horm. Behav. 34, 223–230.

Martel, F.L., Nevison, C.M., Rayment, F.D.G., Simpson, M.J.A., 1994. The social grooming of captive female rhesus monkeys: effects of the birth of their infants. Int. J. Primatol. 15, 555–572.

McLean, M., Smith, R., 1999. Corticotropin-releasing hormone in human pregnancy and parturition. Trends Endocrinol. Metab. 10, 174–178.

Nguyen, T., Diveky, L., Fedirko, B., Kowalski, W., Mehendale, R., Pak, S.C., Parsons, M., Wilson, L., 1999. Diurnal changes in plasma prolactin during the last one third of pregnancy in the baboon. Am. J. Primatol. 47, 231–239.

National Research Council, 1996. Guide for the Care and Use of Laboratory Animals. National Academy Press, Washington, DC.

Nieuwenhuijsen, K., de Neef, K.J., Slob, A.K., 1986. Sexual behavior during ovarian cycles, pregnancy, and lactation in group-living stump-tail macaques (*Macaca arctoides*). Hum. Reprod. 1, 159–169.

Numan, M., Insel, T.R., 2003. The Neurobiology of Parental Behavior. Springer, New York.

Pepe, G.J., Waddell, B.J., Albrecht, E.D., 1990. Activation of the baboon fetal hypothalamic–pituitary–adrenocortical axis at midgestation by estrogen-induced changes in placental corticosteroid metabolism. Endocrinology 27, 3117–3123.

Pryce, C.R., 1992. A comparative systems model of the regulation of maternal motivation in mammals. Anim. Behav. 43, 417–441.

Pryce, C.R., 1993. The regulation of maternal behavior in marmoset and tamarins. Behav. Processes 30, 201–224.

Pryce, C.R., 1996. Socialization, hormones, and the regulation of maternal behavior in nonhuman simian primates. In: Rosenblatt, J.S., Snowdon, C.T. (Eds.), Parental Care: Evolution, Mechanisms, and Adaptive Significance vol. 25. Academic Press, San Diego, CA, pp. 423–476.

Pryce, C.R., Abbott, D.H., Hodges, J.K., Martin, R.D., 1988. Maternal behavior is related to prepartum urinary estradiol levels in red-bellied tamarin monkeys. Physiol. Behav. 44, 717–726.

Pryce, C.R., Dobeli, M., Martin, R.D., 1993. Effects of sex steroids on maternal motivation in the common marmosets (*Callithrix jacchus*): development and application of an operant system with maternal reinforcment. J. Comp. Psychol. 107, 99–115.

Pryce, C.R., Mutschler, T., Dobeli, M., Nievergelt, C., Martin, R.D., 1995. Prepartum sex steroid hormones and infant-directed behaviour in primiparous marmoset mothers (*Callithrix jacchus*). In: Pryce, C.R., Martin, R.D., Skuse, D. (Eds.), Motherhood in Human and Nonhuman Primates, Schultz-Biergert Symposium 3rd, Karger, Basel, pp. 78–86.

Rosenblatt, J.S., 2002. Hormonal bases of parenting in mammals. In: Bornstein, M.H. (Ed.), Handbook of Parenting, Biology and Ecology of Parenting, vol. 2. Lawrence Erlbaum, Mahwah, NJ, pp. 31–60.

Rosenblatt, J.S., Snowdon, C.T. (Eds.), 1996. Parental Care: Evolution, Mechanisms, and Adaptive Significance Academic Press, San Diego, CA.

Seyfarth, R.M., 1980. Social relationship among adult female baboons. Anim. Behav. 28, 798–813.

Silk, J.B., 1987. Correlates of agonistic and competitive interactions in pregnant baboons. Am. J. Primatol. 12, 479–498.

Statsoft, Inc., 1998. STATISTICA for Windows (Computer program manual). Statsoft Inc., Tulsa, OK.

Weaver, I.C.G., Grant, R.J., Meaney, M.J., 2002. Maternal behavior regulate long-term hippocampal expression of BAX and apoptosis in the offspring. J. Neurochem. 89, 998–1002.

Whitten, P.L., Brockman, D.K., Stavisky, R.C., 1998. Recent advances in noninvasive techniques to monitor hormone-behavior interactions. Yearb. Phys. Anthropol. 41, 1–23.