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Oxytocin administration, salivary testosterone, and father–infant social behavior



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ABSTRACT

The growing involvement of fathers in childcare is followed by an increased interest in the neurobiology of fatherhood; yet, experimental work on the neuroendocrine basis of paternal care in humans is limited. The steroid Testosterone (T) and the neuropeptide Oxytocin (OT) have each been implicated in complex social behavior including parenting. However, no study to date explored the interaction between these two hormones in the context of fathering. In the current study we first test the relationship between father's basal salivary T and father and infant's social behaviors during parent–child interaction. Second, we examine the effects of intranasal OT administration on father's T production, and, finally, address the relations between OT-induced change in father's T with father–infant social behavior. Thirty-five fathers and their infants participated in a double-blind, placebo-controlled, within-subject study. Father–infant interaction was micro-coded for paternal and infant social behavior and synchrony was measured as the coordination between their gaze, affect, and vocalizations. Father's salivary T levels were measured at baseline and three times after administration. Results indicate that lower baseline T correlated with more optimal father and infant's behaviors. OT administration altered T production in fathers, relative to the pattern of T in the placebo condition. Finally, OT-induced change in T levels correlated with parent–child social behaviors, including positive affect, social gaze, touch, and vocal synchrony. Findings support the view that neuroendocrine systems in human males evolved to support committed parenting and are the first to describe the dynamic interactions between OT and T within a bio-behavioral synchrony model.

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1. Introduction

Fatherhood has recently become a topic of high social relevance that attracts much public interest (Lamb, 2010). The important shifts in the father's role and involvement in childcare have generated empirical interest in the specific patterns of father–infant interactions and their unique contributions to children's social, emotional, and cognitive growth (Feldman et al., 2013; Flouri, 2005). However, unlike motherhood, research on the hormonal correlates of human paternal care is limited (Gettler et al., 2011b; Gray et al., 2007; Storey et al., 2000). In the current study we focus on two hormones, the steroid Testosterone (T) and the neuropeptide Oxytocin (OT). We first examined associations between basal levels of T and observed father–infant social behaviors. Second, utilizing an experimental design we test how manipulation to one hormone (OT) may lead to alteration in the other (T) and whether this change is associated with specific parent–infant social behavior.

Animal and human research addressed the involvement of T in parental and pair bonding (Kuzawa et al., 2009; van Anders and Goldey, 2010). It has been suggested that alterations in T levels in males reflect a shift between conflicting reproductive strategies and enable men to change from mating efforts to parenting efforts (e.g., Gray and Anderson, 2010). Studies in more than 60 bird species support the 'challenge hypothesis', which suggests that T levels increase when males compete for food and territory and decrease when males need to care for offspring (Wingfield et al., 1990). However, other studies indicate that mating and parenting efforts are not necessarily characterized by distinct endocrine architecture, and that hormonal changes in males that precede mating can occur while paternal child-rearing practices are left un-touched (e.g., Ziegler et al., 2004). Taken together, these findings suggest a modular response of males' androgen system to the changing environment that is not dichotomous but rather flexible and malleable.

Although paternal care is less common in mammals, research in biparental species shows that T levels in fathers decrease in the presence of a dependent offspring (Wynne-Edwards, 2001). For example, marmoset males who carried infants the most had the lowest urinary T levels (Nunes et al., 2001), as well as the greatest declines in gonadal steroids (Nunes et al., 2000). Similarly, exposure to infant scent lowered serum testosterone in father common marmosets (Prudom et al., 2008). This effect was restricted to own-infant (vs. other-infant) scent and was

Abbreviations: ANCOVA, analysis of co-variance; ANOVA, analysis of variance; AUC, area under the curve; CV, coefficient variance; EIA, enzyme immune-assay; IU, international units; OT, oxytocin; OXTR, oxytocin receptor gene; PL, placebo; RSA, respiratory sinus arrhythmia; T, testosterone.

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related to offspring's stage of dependence so that effect was observed with 5–10 day old infants, but not at 3–4 months (Ziegler et al., 2011). In the monogamous and biparental California mouse (*Peromyscus californicus*), greater T-increase during courtship was associated with paternal cuddling and protective repertoire towards their pups (Gleason and Marler, 2010).

Human studies also demonstrate decline in T at the transition to fatherhood, and lower T levels were found in fathers who were more involved in child care (Gettler et al., 2011b; Kuzawa et al., 2009). In a large-scale longitudinal study, Gettler et al. (2011b) tested men's T levels before and after the transition to fatherhood and found that the care of a dependent offspring suppressed men's T. The authors concluded by suggesting that “human males have an evolved neuroendocrine architecture that is responsive to committed parenting” (Gettler et al., 2011b). Tanzanian fathers living in a culture where paternal care is the cultural norm had lower T compared to fathers not involved in caregiving (Muller et al., 2009), and Senegalese fathers highly invested in their children showed lower T compared to uninvolved fathers (Alvergne et al., 2009). Lower T has been related to responsiveness to infant cry (Fleming et al., 2002; Storey et al., 2000), and baby cries decrease men's T only in combination with nurturing responses (van Anders et al., 2012). However, Gettler et al. (2011a) showed no alternation in fathers' T levels during and after interacting with their infant. These findings do not point to disconnection between the endocrine patterns associated with mating and parenting but indicate that T is a flexible steroid hormone that can respond to more than one social stimulus simultaneously.

Research across mammalian species has implicated OT, a nine-amino acid neuropeptide, in parenting and social bonding in mammals (Carter, 2014; Insel, 2010). Human studies have addressed the role of OT in the development of mothering and fathering (for review, Feldman, 2012a). With regard to fathering, studies have shown that paternal social behavior is associated with genetic variations on the oxytocin receptor gene (OXTR) (Feldman et al., 2012); that paternal stimulatory contact with the infant (an index of the sum proportions of proprioceptive touch, stimulatory touch, and exploratory play the father displays) increases OT production in fathers (Feldman et al., 2010a); and that peripheral OT levels in fathers and infants are correlated and the cross-generation link is mediated by father–infant interactive synchrony (Feldman et al., 2010b). Studies applying intranasal OT administration similarly pointed to the effects of OT on observed paternal behavior. For instance, a Dutch study has shown that OT administration increased fathers' exploratory behavior during father–toddler play (Naber et al., 2013).

Our study of fathers and their 5-month-old infants demonstrated that OT administration to the father markedly increased father's salivary OT, respiratory sinus arrhythmia (RSA), and specific fathering behaviors that support social engagement, including touch, social gaze, and re-engagement attempts to maintain infant involvement. OT administration to fathers led to parallel effects on the infant, including increases in infant OT, autonomic readiness, and social behavior (Weisman et al., 2012b). Utilizing a social signal processing methodology, we also showed that OT modulates father's proximity to the infant, father's head speed, and head acceleration during dyadic interaction, and infant's OT reactivity correlated with the father's head acceleration (Weisman et al., 2013a). Consistent with the *bio-behavioral synchrony* model (Feldman, 2012a,b), these findings support the involvement of OT in the development of fatherhood and underscore the mutual influences between paternal OT and father's and infant's micro-level social behaviors.

Although the inter-relationships of OT and T are complex, evidence for such links may be found in animal research. Increased OT binding in the hypothalamus was mediated by estradiol and T in rats (Tribollet et al., 1990); OT increased plasma T levels in squirrel monkeys (Winslow and Insel, 1991); and OT and OT-agonist stimulated T production in Leydig cells isolated from the testis of male rats (Frayne and

Nicholson, 1995). Gossen et al. (2012) showed that exogenous OT increased T levels in young men and suggested that OT may enhance T in order to increase sexual receptivity in intimate contexts. A case study (MacDonald and Feifel, 2012) reporting improved sexual functioning in a married man following prolonged OT administration lends support to this hypothesis. Notwithstanding the relations between lower T and involved fathering, studies of paternal care in Californian mice have shown that rapid T pulses promote paternal behavior (Gleason et al., 2009) and that this process is mediated by the conversion of T to estradiol (E₂) by aromatase (Trainor and Marler, 2002). However, to date, this endocrine process has only been demonstrated in non-human mammals and we are aware that there is no study that tested the effects of exogenous OT on T in fathers.

In light of the above, the current study had three goals. First, we examined the relationships between baseline T and fathers' social behavior and, consistent with our *bio-behavioral synchrony* model, expected not only more paternal behavior in fathers with lower baseline T but also more infant social behavior in such dyads. Second, we measured the effects of OT administration on T production in fathers and hypothesized that OT would alter short-term T levels. Finally, we examined whether OT-induced changes in fathers' T are associated with father–child social behaviors.

2. Materials and methods

2.1. Participants

Thirty-five healthy fathers participated with their infants in two lab visits, a week apart (total $n = 70$). Fathers' exclusion criteria included smoking, chronic mental or physical illness, and medication intake. All fathers were educated middle-class and married to the infant's mother. Infants were healthy, 68.6% were firstborns, and exclusion criteria included premature birth, labor- or birth-related complications, multiple birth, or illness (Table 1). The research was approved by the Institutional Review Board and conducted according to ethical standards, and all participants signed an informed consent. Detailed description can be found in Weisman et al. (2012b).

2.2. Procedure

Fathers were asked to self-administer either OT or placebo (PL) under the supervision of the experimenter. Forty minutes after administration, infant joined father in the observation room for 8 min of well-structured behavioral paradigm (detailed in Weisman et al., 2012b). Father and infant were alone in the room when interaction began approximately 45 min after substance administration. All experiments were held between 1300 h and 1700 h, with the two sessions starting at same time of day.

2.3. Oxytocin vs. placebo

Fathers self-administered 24 IU of either OT (Syntocinon Spray, Novartis, Switzerland; 3 puffs per nostril) or PL. The PL was custom-designed by a commercial compounding pharmacy to match drug minus the active ingredient. Administration order was counterbalanced, and participants and experimenters were blind to drug condition.

Table 1
Fathers' and infants' characteristics.

	Mean (SD)	Minimum	Maximum
Father age (years)	29.70 (4.19)	22	38
Infant age (months)	5.01 (1.25)	3.28	8.11
Infant gender (male/female)	(17/18)		

2.4. Saliva sample collection

Father and infant's saliva samples were collected by the experimenter using Salivette (Sarstedt, Rommelsdorf, Germany) at multiple timepoints: baseline—before substance administration; 40 min after administration prior to interaction; 20 min after interaction began, and 20 min thereafter. Saliva collection was scheduled to allow the assessment of several hormones, including OT, cortisol, and T (see Weisman et al., 2012b, 2013a). Salivettes were immediately stored at -20°C to be centrifuged twice at 4°C at $1500 \times g$ for 15 min within one month. All samples were then stored at -80°C until further processed and then transferred to -20°C . The samples were reconstructed in the assay buffer immediately before analysis.

2.5. Testosterone analysis

Determination of T from saliva samples was performed using a commercial enzyme immune-assay (EIA) kit (ENZO, NY, USA). Measurements were performed in duplicate according to instructions. The concentrations of samples were calculated using MatLab-7 according to the kit's standard curves. The assay's inter-assay and intra-assay coefficients of variance (CVs) were $<11.7\%$. The kit's reported sensitivity is 5.67 pg/ml . However, using Salivette for T determination may have its caveats (e.g., Celec and Ostatníková, 2012; Granger et al., 2004), as compared to the more commonly used method of passive droll.

2.6. Coding father–infant interaction

Interactions were videotaped using Flip Mino HD digital camcorder for off-line coding by trained observers blind to experimental condition. The free-play episode of the interaction was micro-coded for typical social behaviors of fathers and infants, and infants' regulatory capacities, using a computerized system (Noldus, Wageningen, Netherlands). Father behaviors included gaze (either social gaze, i.e., father looking at infant's face; joint attention—both father and infant looking at the same object; gaze to object—father only; gaze avert—father averting from the infant; and father's gaze to infant's body), parental touch (divided into affectionate touch; extremities—touching infant's extreme part of the body; or touch + object which refers to touching the infant and playing with an object at the same time), parental positive affect, and parental vocalization (i.e., infant-directed speech that is high-pitched and of repetitive rhythmic, namely, “motherese”). In parallel, infant behavior included gaze (social gaze—infant looking at father's face or body; joint attention; gaze avert), negative emotionality (expressed in twitched face, sad facial expressions); object manipulation (infant plays with object); and negative vocalization (fussy, cry). The mean duration (in seconds), frequency, proportion (% of time from the entire episode) and latency of each behavior were measured. Behavioral measures were taken from the PL and OT conditions.

2.7. Statistical analysis

Pearson's r correlations were employed to specify the relationship between fathers' basal T and indices of parent–infant social interaction in the PL condition. Intranasal OT effects on salivary T were examined using repeated-measures analysis of variance (ANOVA) analysis with drug condition (OT, PL) and saliva measurement (time: -1 , 40, 65, 85 min) as within variables. Further, baseline T levels and drug order were entered independently and simultaneously as covariates in a repeated ANCOVA analysis to control for alternative explanations. T's area under the curve with respect to ground (AUCg; Pruessner et al., 2003) was calculated between the first and fourth samples, and paired t -tests were computed between the drug conditions. As a secondary analysis aiming to explore associations between OT-induced change in T and social behaviors, percent change of T was calculated using the following formula: $\{(AUCg [OT - PL] / AUCg [PL]) * 100\}$. In order to

overcome the influence of basal T on these relationships we employed a regression model in which T-change was calculated as the unstandardized residuals of a regression analysis with mean basal T as the predictor and percent change in T as the dependent variable (Mehta and Josephs, 2006).

3. Results

3.1. Fathers' basal testosterone is associated with paternal and infant's social behaviors

Baseline T did not differ between the OT and PL conditions, $p > .05$, and showed significant between-conditions correlation, Pearson $r = .39$, $p = .022$. Therefore, the two scores were averaged to create a baseline T composite. Fathers' baseline T was negatively correlated with the frequency and proportion (i.e., total duration) of father's affectionate touch (Fig. 1; Table 2). Similarly, T was negatively correlated with the mean durations of parental vocalization, and positively correlated with the latency to paternal vocalization. This refers to infant-directed speech that is high-pitched and of repetitive rhythmic (i.e., “motherese”). T also correlated with frequency and proportion of father's gaze to infant's body. Finally, fathers' self-reported weekly hours spent with infant was marginally correlated with baseline T, $r = -.33$, $p = .059$. Among infants, paternal T was marginally correlated with shorter mean durations of infant gaze towards father's face (social gaze), with longer latencies to the first social gaze, and with longer periods (mean duration) of infant negative emotionality. Correlations were found also with mean duration, frequency and total proportions of infant's negative vocalization (e.g., cry). Controlling for father's age, the correlations between basal T and paternal behaviors remained unaffected. Finally, father's age negatively correlated with baseline T score, $r = -.38$, $p = .02$.

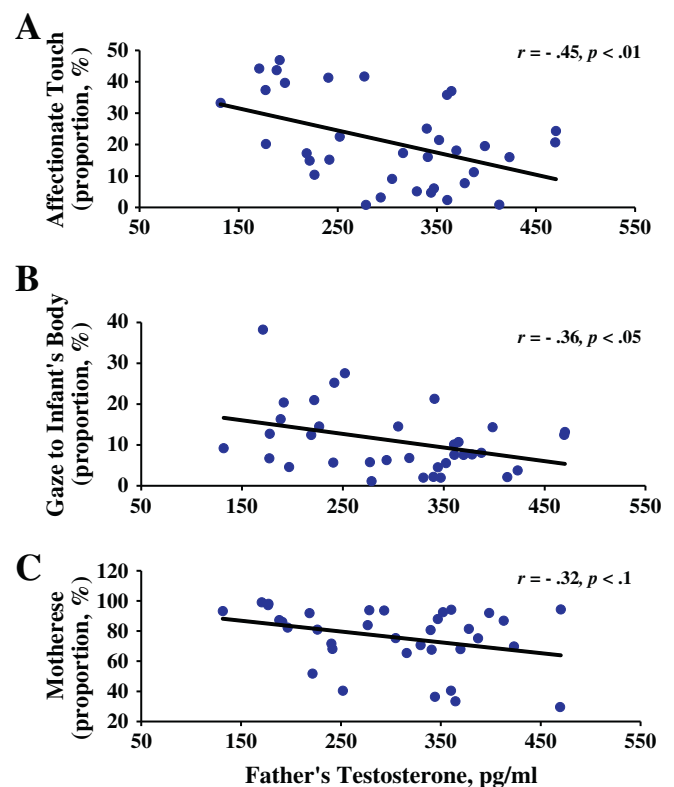


Fig. 1. Scatter plots of the correlations between father's basal Testosterone level (pg/ml) and Father's (A) affectionate touch; (B) gaze to infant's body; (C) infant-directed vocalization (“motherese”).

Table 2

Pearson correlations between father's mean basal testosterone and father–infant social behaviors in the placebo condition.

	Basal T level
<i>Paternal behaviors</i>	
Affectionate touch	
(Frequency)	-.43**
(Proportion)	-.45**
Infant-directed vocalization	
(Mean duration)	-.41**
(Proportion)	-.32†
(Latency)	.35*
Gaze to infant's body	
(Frequency)	-.32*
(Proportion)	-.36*
<i>Infant's behaviors</i>	
Social gaze	
(Mean duration)	-.31†
(Latency)	.38*
Negative emotionality	
(Mean duration)	.30†
Negative vocalization	
(Mean duration)	.34*
(Frequency)	.34*
(Proportion)	.34*

* $p \leq .05$.

** $p \leq .01$.

† $p < .1$.

3.2. Effects of intranasal oxytocin administration on testosterone levels

Significant effect for drug emerged, $F(1,34) = 6.01$, $p = .019$, $\text{Eta}^2 = .15$, with Bonferroni post-hoc comparison showing significantly higher T levels in the OT versus PL condition (OT cond: $M = 284.71$, $SE = 13.23$; PL cond: $M = 251.08$, $SE = 12.5$) (Fig. 2). Significant main effect for drug persisted also when controlling for baseline T in the OT and PL conditions (inserting the two variables as covariates in repeated-measures ANCOVA), $F(1,18) = 5.23$, $p = .034$, $\text{Eta}^2 = .22$, when controlling for drug order (PL first [–.50] vs. OT first [.50]; entered as covariate), $F(1,33) = 6.74$, $p = .014$, $\text{Eta}^2 = .17$, or when controlling for baseline T and drug order simultaneously, $F(1,17) = 6.68$, $p = .019$, $\text{Eta}^2 = .28$. In addition, a significant inverse correlation between baseline T levels and OT-induced percent change in T was found, $r = -.49$, $p = .002$. This negative correlation strengthens current results, by emphasizing that the recorded T-change is not simply a regression to mean, but is actually driven by the drug manipulation itself rather than by the individual's basal T levels.

Further analysis showed no interaction between drug order (OT vs. PL first) and drug condition, drug order and time, or drug order by drug condition by time was found. Computing AUCg further strengthens the finding that OT manipulation alters father's T and paired t-test comparison showing elevated overall T in the OT vs. PL condition,

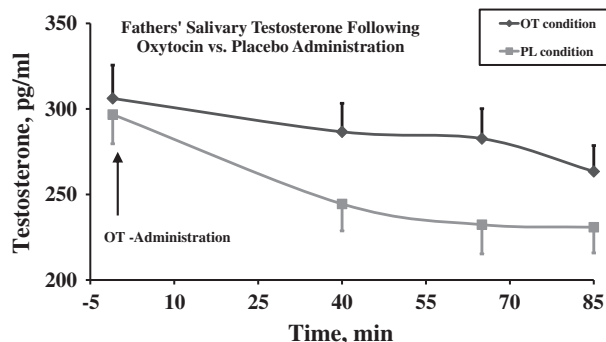


Fig. 2. Salivary Testosterone (pg/ml) of thirty-five fathers following intranasal administration of 24 IU of Oxytocin (OT) vs. Placebo (PL).

$t(34) = 2.63$, $p = .013$. In addition, significant time effect emerged, $F(3,102) = 7.43$, $p = .000$, $\text{Eta}^2 = .18$, suggesting that T decreased along the experiment regardless of drug condition. Further post-hoc comparisons revealed significant difference between baseline T levels (measured at time – 1) and the rest of the samples, suggesting that father's T decreased with time.

3.3. Fathers' change in testosterone levels is associated with parent–infant social behaviors

Pearson correlations between paternal behaviors in the OT condition and OT-induced percent change in fathers' T are presented in Table 3. Importantly, most findings on the associations between T change and dyadic social behaviors held up using an alternative method for calculating change score (unstandardized residuals in the regression model), except for the correlations with joint gaze and vocal synchrony which turned non-significant. Also, to address the possibility that the reported associations between T-change and dyadic behaviors are driven by the link between basal T and the behavioral measures, we conducted regression analysis (Preacher and Hayes, 2004) with behavior as the dependent variable, mean basal T entered at the first step, and T-change entered at the second step. Results show that when controlling for basal T levels, the unique contribution of T-change in predicting behavior remains in most cases.

4. Discussion

Results of the current study extend existing literature by specifying associations between fathers' baseline T levels and a set of well-defined, specific, parent–infant social behaviors that include touch, gaze, affect, and vocalizations. These findings echo animal and human studies showing that paternal repertoire and rearing practices are inversely correlated with T levels in males (e.g., Alvergne et al., 2009; Kuzawa et al., 2009; Muller et al., 2009; Nunes et al., 2000, 2001), as well as with recent work suggesting that T undermines cooperation and affiliation in humans (Mehta et al., 2009; Wright et al., 2012). Consistently, we found that lower baseline T levels in fathers were associated with greater expression of the human parental repertoire, including affectionate touch, gaze, and vocalization, as well as with greater infant social gaze, negative affect, and negative vocalizations. However, it is worthwhile emphasizing that this pattern does not necessarily imply for a disconnection in the endocrine pattern associated with mating

Table 3

(a) Pearson correlations between Oxytocin-induced percent change in father's Testosterone and father–infant social behaviors, and (b) regression analysis predicting father–infant social behaviors in the Oxytocin (OT) condition.

	Pearson r	ΔR^2	β	p
<i>Paternal behaviors</i>				
Positive arousal				
(Latency)	-.39*	.15	-.40	.024
Social gaze				
(Proportion)	.34*	.13	.37	.037
Joint gaze/attention				
(Latency)	-.35*	.07	-.28	n.s.
Gaze to object				
(Frequency)	-.34*	.15	-.39	.023
(Proportion)	-.34*	.14	-.38	.030
Extremities touch				
(Mean duration)	.37*	.15	.39	.027
(Proportion)	.39*	.09	.39	.026
<i>Father–infant synchrony</i>				
Vocal synchrony				
(Frequency)	.38*	.11	.33	.047

For the regression analysis, mean T levels were entered at first step, and percent change in father's T was entered in second step.

* $p \leq .05$.

and parenting efforts, but rather that the T system can simultaneously respond to each.

Second, findings indicate that intranasal OT administration leads to a short-term alteration in T levels among fathers, as compared to fathers' T levels in the PL condition. Whereas research addressing the potential interaction between OT and T has relied mainly on animal studies (Frayne and Nicholson, 1995; Tribollet et al., 1990; Winslow and Insel, 1991), a recent study showed that administration of 26 IU of OT increased T levels in young men 210 min after administration (Gossen et al., 2012). Having that, however, the robust and rapid alteration in T found in the current study (40 min post-administration) may relate to the fact that we assessed fathers' T while socially interacting with their infants—which consequently made them highly responsive to OT manipulation. Other studies have similarly pointed to the effect of OT on circulating levels of some endogenous hormones (Weisman and Feldman, 2013a). For example, OT administration was found to increase plasma and salivary OT levels over a period of up to 7 h (Burri et al., 2008; Gossen et al., 2012; van Ijzendoorn et al., 2012; Weisman et al., 2012a). And, OT has been shown to increase levels of the structurally-related neuropeptide arginine vasopressin (AVP; Weisman et al., 2013c), and to alter levels of salivary cortisol (Ditzen et al., 2009; Weisman et al., 2013b), suggesting an effect of OT on other hormones which are specifically related to paternal care.

Finally, OT-related change in T levels correlated with parental behaviors, including positive arousal, social gaze, and vocal synchrony. These results chart for the first time an association between OT manipulation, baseline and short-term reactivity levels of T, and observed behavior within a bio-behavioral synchrony model that details the mutual influences between affiliative biology and social behavior of parent and child during social contact (Feldman, 2012a,b). Furthermore, the finding that greater change in T is associated with parent and infant's dyadic behaviors is consistent with recent models which suggest that the effects of OT manipulation may be related to increasing social salience and reward from social interactions (Weisman and Feldman, 2013b). The correlations between T-change score and social behaviors within the parental context may represent a “reward” brain response resulting from the interactions of T with the dopamine mesolimbic pathways (Hermans et al., 2010; Mehta and Josephs, 2006), which may facilitate fathers' investment in current reproductive strategy, that is, committed caregiving. Greater T-increase was associated with greater social-behavioral reciprocity between father and infant, indicating greater investment in the parenting context, and possibly these fathers also draw greater reward from father–infant interaction. We recently found (Atzil et al., 2012) that mothers engaged in social gaze synchrony with their infants showed greater brain activations in reward areas (NAcc) and the degree of NAcc activation correlated with the mother's plasma OT, highlighting the relations between reward activation, OT, and social synchrony within the parenting context. Considered together with the finding that fathers with lower baseline T were more sensitive to the OT manipulation (i.e., exhibited greater T increase), it is possible that the functioning of the father's T system, which reflects his investment, enjoyment, and active participation in parenting, shapes his response to the OT manipulation. Such notion is consistent with Gettler et al.'s (2011a,b) view that human males' neuroendocrine system is responsive to committed parenting and extends prior research by adding the individual difference angle and showing that some men's neuroendocrine system may be more responsive to the parenting context than that of others.

The main study limitation relates to the relative small sample size for testing relations between basal T and indices of parent–child interaction. Assessment of additional hormones, particularly biomarkers of the dopamine reward system, would have been able to shed further light on the involvement of reward neuro pathways in mediating the OT–T links. Second limitation concerns the somewhat contradictory finding concerning the inverse correlation between trait-like (basal) T levels and paternal investment in offspring, and the reported link

between OT-driven T increase and enhanced parental repertoire. However, as fathers with lower basal T levels were found to exhibit greater T increase following OT administration, it might very well be that involved male parenting in bi-parental species is characterized by a more sensitive and responsive T system, that further supports or enables the execution of elaborated paternal repertoire. Third limitation relates to method of saliva collection, which is less common than the passive drool (e.g., Celec and Ostatníková, 2012; Granger et al., 2004). Although the kit's instruction does not specify the need to use the passive drool and we conducted comparisons between the two methods with similar results, this is still not the typical method of research and this should be remembered as a study limitation. Additionally, since the current study employed a within subjects design and data is analyzed in the context of the levels detected in each of the experimental conditions, this limitation may be less critical in the current case.

5. Conclusion

Future research is required to test whether OT-induced changes in T may manifest during other periods of bond formation, such as periods of falling in love, and whether the effects of OT on T are sexually dimorphic and are expressed differently in women and men. The dynamic associations between OT and T as they combine to support complex social behavior in humans is an exciting area of research that may shed light on the interactions of the two systems across the lifespan as well as under conditions involving psychopathology of social functioning.

Contributors

Authors OW and RF designed the study. OW ran the experiment. OZS conducted hormonal analyses. OW and RF conducted statistical analyses and wrote the manuscript. All authors contributed to and have approved the final manuscript.

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References

- Alvergne A, Faurie C, Raymond M. Variation in testosterone levels and male reproductive effort: insight from a polygynous human population. *Horm Behav* 2009;56:491–7.
- Atzil S, Hendler T, Zagoory-Sharon O, Weintbrub Y, Feldman R. Synchrony and specificity in the maternal and the paternal brain: relations to oxytocin and vasopressin. *J Am Acad Child Adolesc Psychiatry* 2012;51:798–811.
- Burri A, Heinrichs M, Schedlowski M, Kruger TH. The acute effects of intranasal oxytocin administration on endocrine and sexual function in males. *Psychoneuroendocrinology* 2008;33:591–600.
- Carter CS. Oxytocin pathways and the evolution of human behavior. *Annu Rev Psychol* 2014;65:10.1–10.23.
- Celec P, Ostatníková D. Saliva collection devices affect sex steroid concentrations. *Clin Chim Acta* 2012;9:1625–8.
- Ditzen B, Schaefer M, Gabriel B, Bodenmann G, Ehlert U, Heinrichs M. Intranasal oxytocin increases positive communication and reduces cortisol levels during couple conflict. *Biol Psychiatry* 2009;65:728–31.
- Feldman R. Oxytocin and social affiliation in humans. *Horm Behav* 2012a;61:380–91.
- Feldman R. Parent–infant synchrony: a bio-behavioral model of mutual influences in the formation of affiliative bonds. *Monogr Soc Res Child Dev* 2012b;77:42–51.
- Feldman R, Gordon I, Schneiderman I, Weisman O, Zagoory-Sharon O. Natural variations in maternal and paternal care are associated with systematic changes in oxytocin following parent–infant contact. *Psychoneuroendocrinology* 2010a;35:1133–41.
- Feldman R, Gordon I, Zagoory-Sharon O. The cross-generation transmission of oxytocin in humans. *Horm Behav* 2010b;58:669–76.
- Feldman R, Zagoory-Sharon O, Weisman O, Schneiderman I, Gordon I, Maoz R, et al. Sensitive parenting is associated with plasma oxytocin and polymorphisms in the oxytocin receptor (OXTR) and CD38 genes. *Biol Psychiatry* 2012;72:175–81.
- Feldman R, Bamberger E, Kanat-Maymon Y. Parent-specific reciprocity from infancy to adolescence shapes children's social competence and dialogical skills. *Attach Hum Dev* 2013;5:407–23.
- Fleming AS, Corter C, Stallings J, Steiner M. Testosterone and prolactin are associated with emotional responses to infant cries in new fathers. *Horm Behav* 2002;42:399–413.

- Flouri E. *Fathering and child outcomes*. Chichester, West Sussex, England: Wiley; 2005.
- Frayne J, Nicholson HD. Effect of oxytocin on testosterone production by isolated rat Leydig cells is mediated via a specific oxytocin receptor. *Biol Reprod* 1995;52:1268–73.
- Gettler LT, McDade TW, Agustin SS, Kuzawa CW. Short-term changes in fathers' hormones during father–child play: impacts of paternal attitudes and experience. *Horm Behav* 2011a;60:599–606.
- Gettler LT, McDade TW, Feranil AB, Kuzawa CW. Longitudinal evidence that fatherhood decreases testosterone in human males. *Proc Natl Acad Sci U S A* 2011b;108:16194–9.
- Gleason ED, Marler CA. Testosterone response to courtship predicts future paternal behavior in the California mouse, *Peromyscus californicus*. *Horm Behav* 2010;57:147–54.
- Gleason ED, Fuxjager MJ, Oyegbile TO, Marler CA. Testosterone release and social context: when it occurs and why. *Front Neuroendocrinol* 2009;30:460–9.
- Gossen A, Hahn A, Westphal L, Prinz S, Schultz RT, Gründer G, et al. Oxytocin plasma concentrations after single intranasal oxytocin administration – a study in healthy men. *Neuropeptides* 2012;46:211–5.
- Granger DA, Shirtcliff EA, Booth A, Kivlighan KT, Schwartz EB. The “trouble” with salivary testosterone. *Psychoneuroendocrinology* 2004;29:1229–40.
- Gray PB, Anderson KG. *Fatherhood: evolution and human paternal behavior*. Cambridge, MA.: Harvard University Press; 2010
- Gray PB, Parkin JC, Samms-Vaughan ME. Hormonal correlates of human paternal interactions: a hospital-based investigation in urban Jamaica. *Horm Behav* 2007;52:499–507.
- Hermans EJ, Bos PA, Ossewaarde L, Ramsey NF, Fernández G, van Honk J. Effects of exogenous testosterone on the ventral striatal BOLD response during reward anticipation in healthy women. *Neuroimage* 2010;52:277–83.
- Insel TR. The challenge of translation in social neuroscience: a review of oxytocin, vasopressin, and affiliative behavior. *Neuron* 2010;65:768–79.
- Kuzawa CW, Gettler LT, Muller MN, McDade TW, Feranil AB. Fatherhood, pairbonding and testosterone in the Philippines. *Horm Behav* 2009;56:429–35.
- Lamb ME. *The role of the father in child development*. Hoboken, NJ.: Wiley; 2010
- MacDonald K, Feifel D. Dramatic improvement in sexual function induced by intranasal oxytocin. *J Sex Med* 2012;9:1407–10.
- Mehta PH, Josephs RA. Testosterone change after losing predicts the decision to compete again. *Horm Behav* 2006;50:684–92.
- Mehta PH, Wuehrmann EV, Josephs RA. When are low testosterone levels advantageous? The moderating role of individual versus intergroup competition. *Horm Behav* 2009;56:158–62.
- Muller MN, Marlowe FW, Bugumba R, Ellison PT. Testosterone and paternal care in East African foragers and pastoralists. *Proc Biol Sci* 2009;276:347–54.
- Naber FBA, Poslowsky IE, van Ijzendoorn MH, van Engeland H, Bakermans-Kranenburg MJ. Brief report: oxytocin enhances paternal sensitivity to a child with autism: a double-blind within-subject experiment with intranasally administered oxytocin. *J Autism Dev Disord* 2013;43:224–9.
- Nunes S, Fite JE, French JA. Variation in steroid hormones associated with infant care behaviour and experience in male marmosets (*Callithrix kuhlii*). *Anim Behav* 2000;60:857–65.
- Nunes S, Fite JE, Patera KJ, French JA. Interactions among paternal behavior, steroid hormones, and parental experience in male marmosets (*Callithrix kuhlii*). *Horm Behav* 2001;39:70–82.
- Preacher KJ, Hayes AF. SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behav Res Methods Instrum* 2004;36:717–31.
- Prudom SL, Broz CA, Schultz-Darken NJ, Ferris CT, Snowdon CT, Ziegler TE. Exposure to infant scent lowers serum testosterone in father common marmosets (*Callithrix jacchus*). *Biol Lett* 2008;4:603–5.
- Pruessner JC, Kirschbaum C, Meinlschmid G, Hellhammer DH. Two formulas for computation of the area under the curve represent measures of total hormone concentration versus time-dependent change. *Psychoneuroendocrinology* 2003;28:916–31.
- Storey AE, Walsh CJ, Quinton RL, Wynne-Edwards KE. Hormonal correlates of paternal responsiveness in new and expectant fathers. *Evol Hum Behav* 2000;21:79–95.
- Trainor BC, Marler CA. Testosterone promotes paternal behaviour in a monogamous mammal via conversion to oestrogen. *Proc Biol Sci* 2002;269:823–9.
- Tribollet E, Audigier S, Dubios-Dauphin M, Dreifuss JJ. Gonadal steroids regulate oxytocin receptors but not vasopressin receptors in the brain of male and female rats. An autoradiographical study. *Brain Res* 1990;511:129–40.
- van Anders SM, Goldey KL. Testosterone and partnering are linked via relationship status for women and ‘relationship orientation’ for men. *Horm Behav* 2010;58:820–6.
- van Anders SM, Tolman RM, Volling BL. Baby cries and nurturance affect testosterone in men. *Horm Behav* 2012;61:31–6.
- van Ijzendoorn MH, Bhandari R, van der Veen R, Grewen KM, Bakermans-Kranenburg MJ. Elevated salivary levels of oxytocin persist more than 71/2 h after intranasal administration. *Front Neurosci* 2012;6:174.
- Weisman O, Feldman R. Oxytocin administration affects the production of multiple hormones. *Psychoneuroendocrinology* 2013a;38:626–7.
- Weisman O, Feldman R. Oxytocin effects on the human brain: findings, questions, and future directions. *Biol Psychiatry* 2013b;74:158–9.
- Weisman O, Zagoory-Sharon O, Feldman R. Intranasal oxytocin administration is reflected in human saliva. *Psychoneuroendocrinology* 2012a;37:1582–6.
- Weisman O, Zagoory-Sharon O, Feldman R. Oxytocin administration to parent enhances infant physiological and behavioral readiness for social engagement. *Biol Psychiatry* 2012b;72:982–9.
- Weisman O, Delaherche E, Rondeau M, Chetouani M, Cohen D, Feldman R. Oxytocin shapes parental motion during father–infant interaction. *Biol Lett* 2013a;9(6):20130828. <http://dx.doi.org/10.1098/rsbl.2013.0828>.
- Weisman O, Zagoory-Sharon O, Feldman R. Oxytocin administration alters HPA reactivity in the context of parent–infant interaction. *Eur Neuropsychopharmacol* 2013b. pii: S0924-977X(13)00181-8. <http://dx.doi.org/10.1016/j.euroneuro.2013.06.006> (Epub ahead of print).
- Weisman O, Zagoory-Sharon O, Schneidman I, Feldman R. Salivary vasopressin increases following intranasal oxytocin administration. *Peptides* 2013c;40:99–103.
- Wingfield JC, Hegner RE, Dufty Jr AM, Ball GF. The “challenge hypothesis”: theoretical implications for patterns of testosterone secretion, mating systems, and breeding strategies. *Am Nat* 1990;136:829–46.
- Winslow JT, Insel TR. Social status in pairs of male squirrel monkeys determines the behavioral response to central oxytocin administration. *J Neurosci* 1991;11:2032–8.
- Wright ND, Bahrami B, Johnson E, Di Malta G, Rees G, Frith CD, et al. Testosterone disrupts human collaboration by increasing egocentric choices. *Proc Biol Sci* 2012;279:2275–80.
- Wynne-Edwards KE. Hormonal changes in mammalian fathers. *Horm Behav* 2001;40:139–45.
- Ziegler TE, Jacoris S, Snowdon CT. Sexual communication between breeding male and female cotton-top tamarins (*Saguinus oedipus*) and its relationship to infant care. *Am J Primatol* 2004;64:57–70.
- Ziegler TE, Peterson LJ, Sosa ME, Barnard AM. Differential endocrine responses to infant odors in common marmoset (*Callithrix jacchus*) fathers. *Horm Behav* 2011;59:265–70.