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Fathers' oxytocin responses to first holding their newborns: Interactions with testosterone reactivity to predict later parenting behavior and father-infant bonds

Lee T. Gettler[1,2,3] | Patty X. Kuo[4] | Mallika S. Sarma[5] | Benjamin C. Trumble[6,7] | Jennifer E. Burke Lefever[3] | Julia M. Braungart-Rieker[8]

[1]Department of Anthropology, University of Notre Dame, Notre Dame, IN, USA

[2]Eck Institute for Global Health, University of Notre Dame, Notre Dame, IN, USA

[3]William J. Shaw Center for Children and Families, University of Notre Dame, South Bend, IN, USA

[4]Department of Child, Youth and Family Studies, University of Nebraska-Lincoln, Lincoln, NE, USA

[5]Department of Otolaryngology, School of Medicine, Johns Hopkins University, Baltimore, MD, USA

[6]School of Human Evolution and Social Change, Arizona State University, Tempe, AZ, USA

[7]Center for Evolution and Medicine, Arizona State University, Tempe, AZ, USA

[8]Department of Human Development and Family Studies, Colorado State University, Fort Collins, CO, USA

Correspondence
Lee T. Gettler, 244 Corbett Family Hall, Notre Dame, IN 46556, USA.
Email: lgettler@nd.edu

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Abstract

Little is known about human fathers' physiology near infants' births. This may represent a period during which paternal psychobiological axes are sensitive to fathers' new experiences of interacting with their newborns and that can provide insights on how individual differences in fathers' biology relate to post-partum parenting. Drawing on a sample of men in South Bend, IN (U.S.), we report results from a longitudinal study of fathers' oxytocin, cortisol, and testosterone ($N = 211$) responses to their first holding of their infants on the day of birth and men's reported caregiving and father-infant bonding at 2–4 months post-partum ($N = 114$). First-time fathers' oxytocin was higher following first holding of their newborns, compared to their pre-holding levels. Contrasting with prior results, fathers' percentage change in oxytocin did not differ based on skin-to-skin or standard holding. Drawing on psychobiological frameworks, we modeled the interactions for oxytocin reactivity with testosterone and cortisol reactivity, respectively, in predicting father-infant outcomes months later. We found significant cross-over interactions for (oxytocin × testosterone) in predicting fathers' later post-partum involvement and bonding. Specifically, we found that fathers whose testosterone declined during holding reported greater post-partum play if their oxytocin increased, compared to fathers who experienced increases in both hormones. We also observed a similar non-significant interaction for (oxytocin × cortisol) in predicting fathers' post-partum play. Fathers whose testosterone declined during holding also reported less involvement in direct caregiving and lower father-infant bonding if their oxytocin decreased but greater direct care and bonding if their testosterone increased and oxytocin decreased. The results inform our understanding of the developmental time course of men's physiological responsiveness to father-infant interaction and its relevance to later fathering behavior and family relationships.

KEYWORDS
bonding, cortisol, kangaroo care, paternal psychobiology, skin-to-skin care

1 | INTRODUCTION

For human mothers, pregnancy, birth, and lactation are well-characterized periods of physiological plasticity and change that have wide-ranging effects on the body, including the brain, and are thought to be preparatory for a range of parenting demands (Barba-Müller et al., 2019; Barrett & Fleming, 2011). The importance of maternal hormonal changes to the priming and facilitation of mothering behavior is well-studied in a number of nonhuman species (Numan & Insel, 2003), though we note that these processes remain comparatively understudied and are likely less determinative in human mothers (Barrett & Fleming, 2011). In general, relatively little is known about physiological function in human fathers during the peripartum period. During this time frame, paternal psychobiological axes are potentially responsive to the transition to parenthood (i.e., first-time parents) or the birth/arrival of another child (i.e., experienced fathers) (Edelstein et al., 2017; Kuo et al., 2018; Storey & Ziegler, 2016). Consequently, following birth, fathers' psychobiology may be sensitive to new experiences of interacting with their newborns and their responses to those interactions may provide insights on individual differences in how fathers' biology relates to early post-partum parenting (Garfield et al., 2016; Kuo et al., 2018; Storey et al., 2000).

Conceptually, human fathers' flexible psychobiological responses to partnering and parenting are thought to reflect the importance of paternal care in the evolutionary past, with psychobiological mechanisms helping divert fathers' limited resources (e.g., time and energy) towards parenting effort (Gettler, 2014, 2016; Gray et al., 2017; Rosenbaum & Gettler, 2018; Storey & Ziegler, 2016). For example, in societies in which fathers commonly engage in cooperative caregiving, fathers with lower testosterone have been found to engage in greater direct caregiving, to spend more time in close proximity to their children, including during sleep (cosleeping), and to have less conflict with their partners compared to higher testosterone fathers (Gettler, 2016; Gettler et al., 2020; van Anders, 2013). Paralleling earlier cross-sectional studies (e.g., Gray et al., 2002, 2004), longitudinal research has shown that in these societal contexts men experience biologically-meaningful declines in testosterone as they transition to parenthood, on average. This work has shown the largest decreases in men with newborns (Gettler, McDade, Feranil et al., 2011) and some indication of testosterone rebound across the first-year post-partum (Corpuz & Bugental, 2020), although this may vary across populations (Mazur, 2014; Rosenbaum et al., 2018). Expectant U.S. fathers who experienced larger declines in testosterone during their partners' pregnancies were more engaged in infant care post-partum and their partners reported that the fathers helped more with household tasks and that they felt more supported and satisfied (Edelstein et al., 2017; Saxbe et al., 2017). In a separate study, U.S. fathers with lower testosterone the day after their child's birth reported being more involved with direct and indirect childcare months later at a longitudinal follow-up (Kuo et al., 2018).

These past longitudinal studies highlight the importance of the peripartum period, as men transition from expectant fathers to parents of newborns, as a time frame of physiological plasticity, with

potential implications for later parenting responsibilities. These prior studies have also primarily focused on men's basal hormone production, with research designs broadly intended to measure men's average, day-to-day hormone levels (Kuo & Gettler, 2018). However, hormone axes related to the psychobiology of parenting, including testosterone but also hormones such as oxytocin, prolactin, and cortisol, also respond to specific social interactions and contexts acutely and rapidly (e.g., over 15–60 min) (Kuo & Gettler, 2018; Rilling & Mascaro, 2017; Trumble et al., 2015). For example, fathers' cortisol has been found to decline during fathers' first holding of their newborns on their day of birth as well as in response to father-toddler play (Gettler, McDade, Agustin et al., 2011; Kuo et al., 2018; Storey et al., 2011). Fathers' oxytocin was also shown to increase in response to father-infant play (Feldman, Gordon, Schneiderman, et al., 2010; Feldman, Gordon, & Zagoory-Sharon, 2010). Elsewhere, fathers' testosterone has been observed to increase in response to audio recordings of infant cries (Fleming et al., 2002), particularly in the early post-partum, which has been interpreted as a physiological response that may help increase paternal protectiveness (Storey et al., 2000; see also Roellke et al., 2019; van Anders et al., 2012).

Along these lines, there is evidence linking these short-term hormonal responses to variation in fathers' concurrent parenting behaviors. For example, Kuo et al. (2016) found that fathers who exhibited a short-term decline in testosterone during the separation portion of the Strange Situation subsequently engaged in more positive parenting behaviors during a challenging teaching task. In a home-based research design, fathers who spent more time interacting with their toddlers during a 30-min period exhibited greater concurrent declines in testosterone (Storey et al., 2011). In two studies that involved having men interact with life-like dolls with their settings programmed to various levels of distress, it was found that larger short-term declines in men's testosterone coincided with greater expression of nurturant behavior (Roellke et al., 2019; van Anders et al., 2012). Finally, in multiple studies, fathers receiving exogenous, intra-nasal oxytocin subsequently engaged in greater nurturing behaviors, such as affectionate touch, positive encouragement, and sensitivity (Naber et al., 2013; Weisman et al., 2012b). These effects potentially occur through areas of the brain involved with reward processing and empathy (Li et al., 2017; Rilling & Mascaro, 2017), although we note that it is important to contextualize these patterns within the broader literature on psychobiological effects of intra-nasal oxytocin, including methodological and biological considerations and limitations (Quintana et al., 2020). In contrast, a small number of other studies have explored correlations between fathers' routine, day-to-day caregiving (i.e., in comparison to behaviors occurring concomitant to the hormone changes) and hormonal reactivity to father-child interaction and have found limited evidence (testosterone) or mixed evidence (cortisol) for such a link (Gettler, McDade, Agustin et al., 2011; Kuo et al., 2016, 2018).

One possibility that is largely unexplored but generally aligns with psychobiological frameworks (van Anders et al., 2011) is that fathers' hormonal reactivity to family social contexts is relevant to their routine parenting behaviors but that those linkages are difficult

to detect through designs focused on individual hormone responses. It is widely-accepted that complex social phenomena are typically affected by multiple signals and systems within the body that make additive, interactive, or antagonistic contributions to behavioral, emotional, and cognitive functions (Bos, 2016; Chen et al., 2015; van Anders et al., 2011). Psychobiology research on parents' basal hormone profiles has increasingly explored this combinatorial perspective (Bos et al., 2018; Gettler et al., 2019; Gordon et al., 2017). Specifically, testosterone and oxytocin are two signals that potentially contribute interactively to the expression of nurturant, warm parenting and partnering, i.e., in individuals with higher oxytocin and lower testosterone (van Anders et al., 2011). For example, in an Israeli study of basal hormone levels, for fathers with higher oxytocin, those who also had higher testosterone engaged in less affectionate touch during observed interactions, compared to those with lower testosterone (Gordon et al., 2017).

In addition, a small number of studies have also considered the additive and interactive effects of oxytocin and cortisol on family interactions. In research with Israeli families, mothers and fathers with higher oxytocin engaged in more synchronized family interaction. Mothers with lower cortisol also exhibited greater synchrony, but oxytocin and cortisol did not interact to predict family interactions for either parent (Gordon et al., 2010). In a separate study, Israeli fathers who received exogenous intranasal oxytocin showed greater short-term cortisol increases during a challenging parent-infant interaction (the Still Face Paradigm), compared to their placebo responses (Weisman et al., 2013). The authors suggested this result was consistent with the "social salience" hypothesis for oxytocin, which is premised on the idea that the hormone focuses individuals' attention on socially salient stimuli and interactions, regardless of valence (Bartz et al., 2011; Weisman et al., 2013). In both mothers and fathers, higher cortisol specifically in the early post-partum has been linked to more affection and sensitivity (Fleming et al., 1987; Stallings et al., 2001) and greater involvement in play and indirect care (Kuo et al., 2018). During the early post-partum it is plausible that greater oxytocin production helps to enhance cortisol's promotion of parents' focus and responsiveness to infant cues and needs (Almanza-Sepulveda et al., 2020; Kuo et al., 2018), though this may not apply to cortisol measured at time points outside of the early post-partum (Bos et al., 2018).

Here, we explored oxytocin responses to U.S. fathers' first physical contact with their newborns, shortly following birth, and the interaction between oxytocin reactivity during this contact with testosterone and cortisol reactivity, respectively, in predicting parenting later in the post-partum. Specifically, building from our prior work that focused on main effects of fathers' cortisol and testosterone, respectively, in predicting paternal caregiving (Kuo et al., 2018), we drew on hormone data collected from a large sample (N = 211) of U.S. fathers during their first holding of their newborn and follow-up data reported by a sub-set of fathers (N = 114) at 2–4 months post-partum on their paternal involvement and father-infant bonding. To position our work relative to other research on parents' oxytocin and skin-to-skin newborn contact (e.g., Vittner et al., 2018), we first

tested the prediction that fathers' oxytocin would be higher following first holding of their newborns, particularly for fathers engaging in skin-to-skin contact (vs. standard holding) and first-time fathers. We then tested the hypothesis that oxytocin reactivity would moderate the relationship between testosterone reactivity and cortisol reactivity, respectively, in predicting later parenting outcomes. We specifically predicted that for fathers whose oxytocin increased during holding, the relationships between testosterone reactivity and fathers' post-partum involvement and bonding, respectively, would be more strongly negative, particularly compared to fathers with oxytocin declines. In addition, we predicted that fathers showing oxytocin increases during holding would exhibit a stronger positive relationship between cortisol reactivity and post-partum parenting outcomes, especially relative to fathers whose cortisol and oxytocin both decreased.

2 | MATERIALS AND METHODS

2.1 | Study population

The current study focuses on data collected from 211 fathers whose infants were born at local hospital in South Bend, IN during 2015–2016. The design included a longitudinal follow-up with a sub-set of fathers (N = 114) at 2–4 months post-partum. We report descriptive statistics for the longitudinal, follow-up sample in the current study in Table 1. The sample sizes in the present report are somewhat smaller than the original study, including our prior published results (e.g., N = 298 vs. N = 211), because the current analyses focus on salivary oxytocin, which we analyzed secondarily for men who had sufficient remaining saliva after our initial analysis of salivary cortisol and testosterone (Kuo et al., 2018). Hospital staff on the child-birthing unit recruited fathers following the admission of mothers to the unit. Men were eligible for inclusion in the study if they identified as the father of infant (regardless of biological relatedness), were 18 years of age or older, and their infant was born at Memorial Hospital in South Bend, Indiana, U.S. The Institutional Review Boards at the University of Notre Dame and Memorial Hospital approved all procedures for the study and all participants provided written informed consent. Because our present analyses drew on similar data as our prior work from this study, our methods are comparable to an earlier report (Kuo et al., 2018).

2.2 | Study procedures

Memorial Hospital is a UNICEF-designated "baby-friendly" hospital. As part of the baby-friendly initiative, mothers are encouraged to engage in skin-to-skin contact for an hour immediately following the infant's birth. Following this skin-to-skin contact with mothers, fathers in the present study were then also encouraged to hold their newborns for up to an hour and could choose whether they engaged in skin-to-skin contact or standard holding during that time

TABLE 1 Descriptive statistics for the follow-up sample[a]

Sociodemographics	Follow-up sample	
	Mean	SD
Fathers' age (years)	31.94	5.59
Estimated annual household income	$86,456.97	$43,645.49
Fathers' education level		
Less than 4-year college degree (%)	48.2	—
4-year college degree or more (%)	51.8	—
Parity & biological relatedness		
First-time father (% yes)	45.1	—
Biological father (% yes)	100.0	
Marital & residential status		
Married (% yes)	83.0	—
Residing with infant's mother (% yes)	99.1	—
Race and ethnicity		
Black/African American (%)	7.3	—
Multi-racial (%)	3.7	—
White (%)	89.0	—
Infant characteristics		
Sex (% female)	45.6	—
Infant age at follow up (weeks)	11.66	6.54
Birthing unit holding data		
Skin-to-skin holding (% yes)	46.0	—
Total holding time (min)	26.31	17.16
Post-partum paternal care and bonding		
Direct caregiving (% of activity)	23.57	11.51
Play (% of activity)	34.60	13.75
Father-infant bonding score	78.73	9.34
Hormone data		
Pre-holding oxytocin (pg/ml)	79.58	86.24
Post-holding oxytocin (pg/ml)	90.09	93.51
Oxytocin reactivity (%)	28.70	67.22
Pre-holding T (pg/ml)	80.87	32.73
Post-holding T(pg/ml)	75.55	30.24
T reactivity (%)	−3.13	27.69
Pre-holding cortisol (μg/dl)	0.17	0.16
Post-holding cortisol (μg/dl)	0.12	0.15
Cortisol reactivity (%)	−12.07	70.10

[a]We report descriptive statistics for the follow-up sample of fathers with full hormone data (N = 114). Some fathers were missing values for certain demographic data (Ns = 103–109) as well as father-infant bonding (N = 106) and biological relatedness (N = 88).

frame. In the present analyses focusing on oxytocin on the birthing unit, ~49% of fathers engaged in skin-to-skin care with ~51% opting to participate in standard holding; the average holding time was 29.84 min ± 30.03 (SD). Fathers who engaged in standard holding held their newborns for a mean of 26.96 min ± 17.35, while those engaging in skin-to-skin contact held their infants for 32.86 min ± 38.97, on average. There was not a significant difference in holding time between the two groups (p > .1; also see Table S2). Three men (of N = 211) could not be coded as either engaging in standard or skin-to-skin holding. During the time period when fathers were holding their newborns, other family members, including older children, could have been present in the birthing room. We do not have data on these contextual dynamics.

We collected saliva samples from men before and after they first engaged with their newborns on the birthing unit. Given that babies can be born at any time during the 24-h day, the collection time for the first sample ranged from 12:02 a.m. to 11:59 p.m. Prior to providing their first saliva sample, men filled out a basic sociodemographic survey. During the recruitment and data collection at the hospital, we also invited fathers to participate in an online follow-up study via Qualtrics to assess fathers' well-being and parenting as well as father-infant bonding. We initially began contacting fathers at 2 months post-partum and attempted to collect follow-up data within a 2–4 month time frame, which coincides with early development of parent-infant attachment (Feldman, 2012a). Of the original recruited sample who were eligible for these oxytocin-focused analyses (N = 211), ~59% participated in the follow-up study, which closely aligns with the follow-up recruitment rates in the overall study (~60%; Kuo et al., 2018), and ~94% of the fathers' responses occurred within 16 weeks of discharge. Seven fathers completed the follow-up beyond 16 weeks. We do note that small numbers of otherwise-eligible men had incomplete data for certain demographic variables (e.g., 5 of 211 did not report whether they were experienced fathers at initial recruitment).

2.3 | Paternal care

In the follow-up survey at 2–4 months, fathers estimated their involvement from 0 to 100% in care behaviors for the infant, compared to mothers or other caregivers, using the Childcare Activities Scale (Cronenwett et al., 1988). Fathers reported on their involvement in direct care (eight items, α = .65, e.g., "Bathing child", "Dressing child") and play (six items, α = .80, e.g., "Playing actively with child"). This survey also includes an indirect care sub-scale (e.g., "Arranging babysitting"). Given the focus of the current analyses on fathers' hormone reactivity to early parent-infant interaction we predicted the interactive post-partum caregiving behaviors (direct care; play) as conceptually linked outcome variables.

2.4 | Father-infant bonding

At follow-up, fathers also reported on their bonding with their infants through the Paternal-Infant Attachment Scale (Condon et al., 2008). We used the total score from this 19-item instrument (α = .86), with

each item having a five-point response scale. For example, fathers are asked, "Over the last 2 weeks I would describe my feelings for the baby as", with responses ranging from "dislike" to "intense affection," and "I can understand what my baby needs or wants," with responses from "almost never" to "almost always."

2.5 | Saliva collection and hormone assays

Participants provided saliva samples via passive drool into 2 ml polypropylene tubes. Samples were immediately frozen in a −20°C freezer, and then team members transported them frozen, generally within 7–14 days of collection, to a −80°C freezer at The Hormones, Health, and Human Behavior Laboratory at the University of Notre Dame. We aliquoted (partitioned) the samples from the 2 ml tubes into smaller polypropylene micro-centrifuge tubes to allow for staged analyses over time, storing the aliquots at −80°C. For cortisol and testosterone assays, we then shipped saliva aliquots on dry ice to Salimetrics, where they were assayed using ELISA procedures designed for saliva. For cortisol, the inter-assay coefficients of variation (CVs) were 8.3% (low control) and 9.4% (high control) while the intra-assay CVs were 5.0% (low) and 4.0% (high). The inter-assay CVs for the low and high control values for testosterone were 13.6% and 10.1%, respectively. The intra-assay CVs for testosterone were 6.7% (low) and 2.5% (high). We also shipped saliva aliquots to Dr. Benjamin Trumble and colleagues at the CompHEALTH Lab at Arizona State University, where they were analyzed for oxytocin using commercially-available kits (Enzo Life Sciences, Kit Number: ADI-900-153A). The inter-assay CVs were 21.7% (low) and 19.3% (high). The intra-assay CVs were between 11.5%–15.0%. The salivary oxytocin data were not extracted. Extraction has been identified as a key methodological step for blood-based oxytocin measures, as extracted versus unextracted oxytocin values can differ by orders of magnitude (McCullough et al., 2013). As MacLean et al. (2019) note, the pharmacokinetics of salivary oxytocin merit further exploration; however, our unextracted results in the present study are relatively similar to extracted values from men in a separate earlier study using the same commercially-available assay kits (Jaeggi et al., 2015). In our initial analyses focusing solely on oxytocin, we natural log-transformed the pre-holding and post-holding oxytocin variables because their distributions were skewed. For oxytocin, cortisol, and testosterone reactivity, respectively, we calculated percentage change scores in each hormone from pre- to post-holding. We statistically adjusted the hormone reactivity scores for their sampling times. These adjustments were conducted by regressing the reactivity score on the times of sample collection. For each model, we then predicted the residuals and added the original dependent variable's mean to the residuals, which removes the effect of the independent variable on the dependent variable (Gettler et al., 2012). We excluded two saliva samples from the analyses based on a cortisol percentage change score that was biologically implausible and a substantially elevated pre-holding cortisol value, respectively, with both issues potentially indicating blood contamination (both values were 11+ SDs above the mean).

2.6 | Statistical analyses

We conducted all statistical analyses using Stata 14.0 (Stata Corporation). We first ran bivariate correlational analyses (Pearson's *r*) between key study variables and report those results in Table S1. We then used linear mixed models with maximum likelihood estimation (Stata's "mixed" command) to predict men's log-transformed oxytocin from time point (pre- vs. post-holding), paternal experience (first-time vs. experienced fathers), and holding type (skin-to-skin vs. standard holding). In each model, we included a random intercept effect for each father to account for the repeated sampling in the study design (i.e., pre- vs. post-holding). We conducted two model sets. In model set 1, we tested for bivariate main effects of: time point, paternal experience, and holding type. In model set 2, we included interactions between (paternal experience × time point) and (holding type × time point). We then used pairwise comparisons to further evaluate the patterns for pre- and post-holding based on those categories. We also conducted complementary comparisons of fathers' oxytocin reactivity (percentage change in oxytocin) using unpaired *t*-tests based on whether they were experienced versus first-time fathers or engaged in skin-to-skin or standard holding of their newborns.

We then ran a series of model sets predicting each post-partum parenting outcome from the interaction between (oxytocin reactivity × testosterone reactivity) and (oxytocin reactivity × cortisol reactivity), respectively. We ran initial models using ordinary least squares regression and inspected the results using leverage versus squared residual plots (via Stata's "lvr2plot" command). An lvr2plot is a regression diagnostic procedure used to identify data points that have substantial effects on the pattern of the results, which are often due to outlying values (https://www.stata.com/manuals/rregresspostestimationdiagnosticplots.pdf). The lvr2plots identified a small number of influential points in the cortisol analyses, particularly predicting fathers' direct caregiving, but the relevant percentage change values for cortisol reactivity were biologically plausible. Consequently, we ran our subsequent models using robust regression using the "rreg" command in Stata. The first model included only the core interaction term and the relevant main effects. In the second model, we added fathers' age as a covariate in relevant models (see next paragraph). Finally, in models for father-infant bonding, we added fathers' play and direct caregiving as independent variables that could be in the pathway between fathers' hormone reactivity and bonding. We used the "margins, dydx" command in Stata to conduct Simple Slope analyses following interaction effects, using the standard convention of −1 SD and +1 SD for the values of the moderator variable (oxytocin reactivity). We evaluated significance at *p* ≤ .05.

2.6.1 | Covariates and model selection

In order to avoid overfitting the core regression models in our analyses, we identified theoretically- and empirically-supported covariates that could potentially confound or help to explain links between fathers' hormone reactivity and post-partum parenting outcomes, including: paternal experience, skin-to-skin or standard holding, paternal age, and infant's age at follow-up. We evaluated their associations with our primary outcomes of interest and our core predictors (fathers' hormone reactivity; Tables S1 and S2). As we show in bivariate analyses in Table S2, men eligible for the present analyses did not differ for hormone reactivity based on skin-to-skin versus standard holding or paternal experience (all p > .2). Using Akaike information criterion (AIC) and Bayesian information criterion (BIC), our inclusion of holding type or paternal experience as covariates did not substantially improve the model fit for any analyses. Similarly, infants' age at follow-up was not meaningfully correlated to our primary dependent or independent variables and including it as a covariate did not improve model fit. Fathers' age was linked to post-parenting outcomes and its inclusion as a covariate generally improved model fit for analyses involving testosterone; none of the covariates we considered improved the model fit for analyses involving cortisol. We included fathers' age in the relevant models and report each model's AIC and BIC values.

3 | RESULTS

3.1 | Linear mixed models comparing fathers' pre-holding versus post-holding oxytocin

In model set 1 focusing on main effects of time point, paternal experience, and holding type, we found that there was no significant difference between experienced and first-time fathers for log-transformed oxytocin, aggregating the values from both pre- and post-holding (p > .2; Table 2). Similarly, there was no significant main effect of holding type (p > .1). However, fathers' post-holding oxytocin was significantly higher than their pre-holding levels (p = .001; Figure 1; Table 2), which descriptively aligns with the overall pattern that fathers exhibited a mean percentage increase in pre-to-post oxytocin of +31.0%

(±72.8% SD). In model set 2, we tested for interactions between time point with paternal experience and holding, respectively, and evaluated pairwise comparisons for key variables. In these models, there was a significant conditional main effect for time point, with post-holding oxytocin being higher than pre-holding (p = .001). Similarly, there was a conditional main effect for paternal experience, such that experienced fathers had higher oxytocin than first-time fathers (p = .036; Figure 1; Table 2). However, in pairwise comparisons, the significant oxytocin difference between experienced and first-time fathers was restricted to pre-holding (p < .001) but not observed for post-holding levels (p > .2). Moreover, first-time fathers' post-holding oxytocin was significantly higher than their levels pre-holding (p < .001), whereas experienced fathers' pre versus post-levels did not significantly differ (p > .2; Figure 1). In addition, fathers who engaged in skin-to-skin holding did not have higher post-holding oxytocin, compared to pre-holding (p > .1), while men who participated in standard holding did exhibit a pre- to post-holding increase (p < .01). There was not a significant difference for slope of change between skin-to-skin and standard holding, however (p > .3; Table 2).

In addition, we note that men's percentage change in oxytocin, which is a core predictor in the models reported below, did not significantly differ based on skin-to-skin (N = 101) versus standard holding (N = 107; unpaired t-test; $t(df)$ = 0.94(206); p > .3) or first-time (N = 96) versus experienced father (N = 110; $t(df)$ = 1.50(204); p > .1). For the men in the longitudinal follow-up (N = 113), we found similar non-significant results for the comparison of percentage change in oxytocin based on paternal experience and holding type (both p > .4; Table S2).

### 3.2 | Interaction models predicting fathers' post-partum parenting and father-infant bonding

3.2.1 | Direct caregiving

In our initial model predicting fathers' direct caregiving from the interaction of (oxytocin reactivity × testosterone reactivity), we found that the interaction term was significant (p = 0.023; Table 3). For fathers whose oxytocin declined during holding, there was a positive slope relating testosterone change to fathers' direct

TABLE 2 Linear mixed models predicting fathers' log-transformed oxytocin on the birthing unit

	Model set 1: Main effects				Model set 2: Interaction effects			
	coef	95% CI	p	N (obs)	coef	95% CI	p	N (obs)
Time point (post-holding vs. pre-holding)	**0.14**	**(0.06, 0.23)**	**.001**	**211 (422)**	**0.27**	**(0.11, 0.44)**	**.001**	**203 (406)**
Experienced father (vs. first-time father)	0.14	(−0.09, 0.36)	.227	206 (412)	**0.26**	**(0.02, 0.50)**	**.036**	**203 (406)**
Skin-to-skin holding (vs. standard holding)	0.15	(−0.07, 0.37)	.184	208 (416)	0.23	(−0.01, 0.48)	.060	203 (406)
Experienced father × time point					−0.17	(−0.35, 0.01)	.058	203 (406)
Skin-to-skin holding × time point					−0.09	(−0.26, 0.09)	.340	203 (406)

Results in bold indicate statistically significant findings.
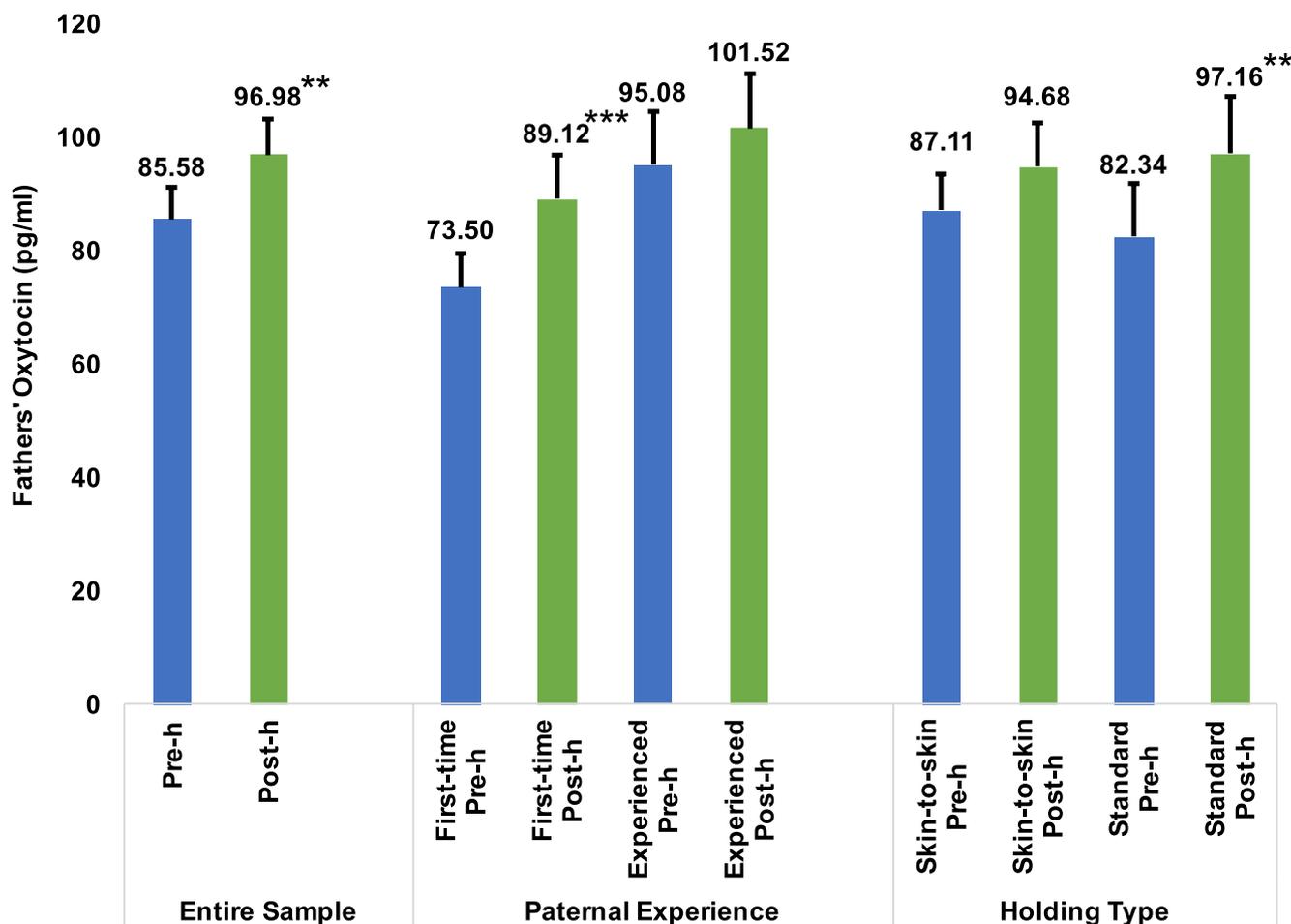
FIGURE 1 Comparisons of men's pre-holding oxytocin and post-holding oxytocin on the Child Birthing unit, for the entire sample and stratified by paternal experience and holding type. First-time, first-time father; Experienced, experienced father; Post-h, post-holding; Pre-h, pre-holding; Skin-to-skin, skin-to-skin holding; Standard, non-skin-to-skin holding. In the Results, we report outcomes of linear mixed models predicting fathers' log-transformed oxytocin, and the indicators of significant differences in the figure reflect the within-individual analyses from those models. Here, we present raw oxytocin values for visual purposes. **p < .01, ***p < .001; Error bars indicate SE

caregiving; the simple slopes analysis for this effect was significantly different from zero (*p* < .001). For fathers whose testosterone increased during holding, there was a mildly positive slope relating oxytocin change to direct caregiving and the simple slopes analysis was not significant (*p* > .1; see Figure 2). This moderation effect was largely unchanged when we adjusted for fathers' age. There was a positive main effect for testosterone reactivity in both models (both *p* < .01; Table 3). In analogous analyses for (oxytocin reactivity × cortisol reactivity), we found no significant results for direct caregiving (all *p* > .3).

3.2.2 | Play

In similar models predicting fathers' post-partum play, we observed a significant crossover interaction for (oxytocin reactivity × testosterone reactivity; *p* = .005). For fathers whose oxytocin declined during holding, there was positive slope relating testosterone to play, but the simple slope analysis was not significant (*p* > .1). In

those whose oxytocin increased, the slope relating testosterone to play was negative (Figure 2), and the simple slopes analysis was significant (*p* = .046). When we adjusted this model for fathers' age, the results for the interaction term changed minimally (*p* = .004; Table 3).

In analyses for (oxytocin reactivity × cortisol reactivity), we also found a cross-over interaction predicting fathers' play, although it was not statistically significant (*p* = .052; Figure 3). The simple slopes analyses for this interaction were also not statistically significant (both *p* > .05). In fathers whose oxytocin declined during holding the slope relating cortisol reactivity to play was positive, though non-significant (*p* = .09). For fathers whose oxytocin increased, the slope relating cortisol reactivity and play was non-significant and negative (*p* = .198).

3.2.3 | Father-infant bonding

Finally, in models predicting father-infant bonding, we found a significant interaction for (oxytocin reactivity × testosterone reactivity; *p* = .046) and a significant positive main effect for testosterone

TABLE 3 Robust regression models predicting fathers' post-partum involvement in direct caregiving and play from interactions between their hormone reactivity change scores during newborn holding

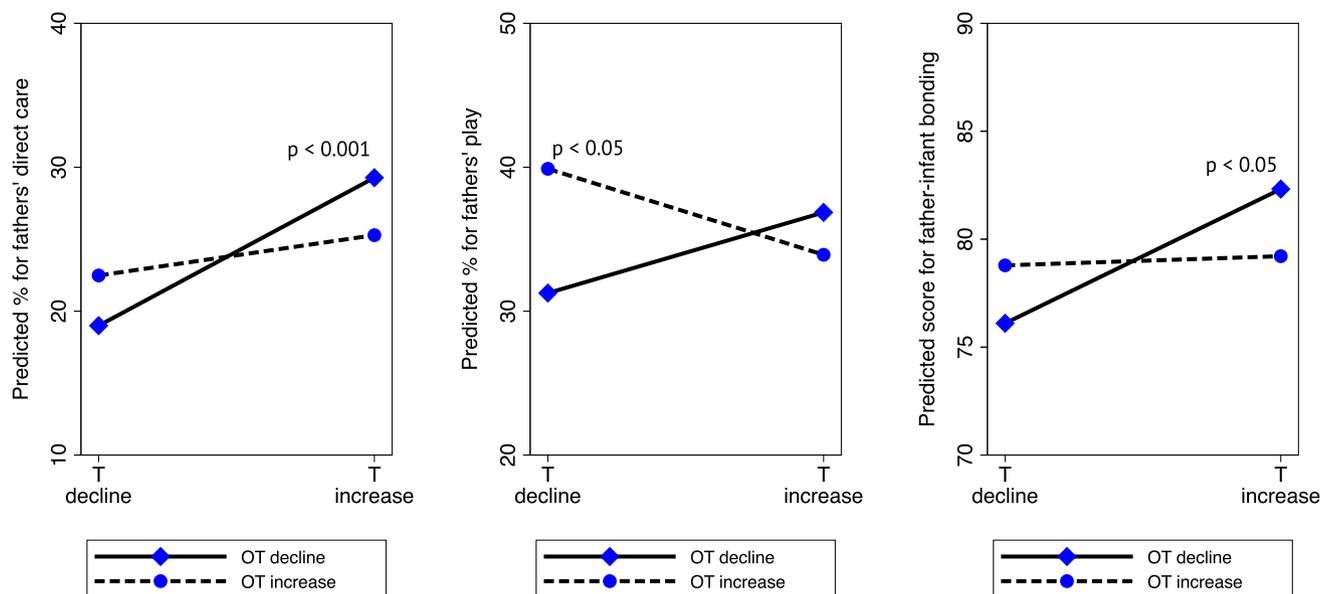| | Oxytocin and testosterone reactivity | | | | | |
| | Model 1 (N = 114) | | | Model 2 (N = 106) | | |
	b	95% CI	*p*	*b*	95% CI	*p*
Direct caregiving						
Oxytocin	−0.01	(−0.04, 0.03)	.687	−0.004	(−0.04, 0.03)	.811
Testosterone	**0.17**	**(0.07, 0.26)**	**.001**	**0.14**	**(0.04, 0.25)**	**.006**
Oxytocin × testosterone	**−0.001**	**(−0.002, −0.0002)**	**023**	**−0.001**	**(−0.002, −0.0002)**	**.012**
Fathers' age				**−0.73**	**(−1.11, −0.35)**	**.0002**
Model R^2		0.10			0.20	
AIC & BIC		AIC 89.13	BIC 102.57		AIC 83.73	BIC 99.95
Play						
Oxytocin	0.01	(−0.03, 0.05)	.682	0.02	(−0.02, 0.06)	.375
Testosterone	0.05	(−0.06, 0.15)	.410	0.01	(−0.11, 0.14)	.838
Oxytocin × testosterone	**−0.002**	**(−0.003, −0.001)**	**.005**	**−0.002**	**(−0.003, −0.001)**	**.004**
Fathers' age				**−0.62**	**(−1.09, −0.15)**	**.010**
Model R^2		0.07			0.12	
AIC & BIC		AIC 91.98	BIC 105.42		AIC 103.73	BIC 119.10
	Oxytocin and cortisol reactivity					
	Model 1 (N = 114)					
	b		95% CI			*p*
Play						
Oxytocin	−0.02		(−0.06, 0.02)			.391
Cortisol	0.02		(−0.02, 0.06)			.304
Oxytocin × cortisol	−0.001		(−0.001, 0.0001)			.052
Model R^2			0.05			
AIC & BIC			AIC 98.41			BIC 111.55

Note: All hormone variables (oxytocin, testosterone, and cortisol) refer to percentage change reactivity scores. Results in bold indicate statistically significant findings.

Abbreviations: AIC, Akaike information criterion; BIC, Bayesian information criterion.

reactivity (*p* = .044; Figure 2). For fathers whose oxytocin declined during holding, there was positive slope relating testosterone to father-infant bonding, and the simple slope analysis was significant (*p* = .022). For men whose oxytocin increased, the line of best fit relating testosterone reactivity to bonding was relatively flat, and the simple slopes analysis was not significant (*p* > .8). When we adjusted the model for fathers' ages, the interaction (*p* = .058) and main effect for testosterone (*p* = .122) were no longer statistically significant. Although the core predictors were no longer significant in this second model, we added fathers' direct caregiving and play as potential explanatory variables to assess changes in the overall pattern of the effects. As shown in Table 3, in that final model, the effect sizes linking (oxytocin reactivity × testosterone reactivity) and testosterone reactivity to father-infant bonding were further attenuated. In models for (oxytocin reactivity × cortisol reactivity), there were no significant associations with father-infant bonding (all *p* > .1).

4 | DISCUSSION

In the present analyses, we drew on a longitudinal study design to test whether fathers' physiological reactivity for key parental hormones (oxytocin, testosterone, and cortisol) in response to their first interactions with their newborn predicted later post-partum parenting outcomes. We tested for interactions between fathers' hormonal reactivity in relationship to post-partum parenting, based on psychobiological concepts related to the combinatorial effects of multiple physiological systems on social phenomena, including nurturing parenting (Bos, 2016; Chen et al., 2015; van Anders et al., 2011). We found support for consistent interactive effects between oxytocin and testosterone reactivity in predicting fathers' post-partum involvement and father-infant bonding. In the subsequent sections, we contextualize these results within psychobiological framing and empirical research regarding expression of parenting in the early post-partum.

FIGURE 2 Men's post-partum direct caregiving, play, and father-infant bonding scores predicted from (oxytocin reactivity × testosterone reactivity). The plots were derived using predictive margins (adjusted predictions) following the Model 1 robust regression analyses in Tables 3 and 4 for (oxytocin reactivity × testosterone reactivity). For visual purposes, we present predicted fathering outcomes based on fathers having relatively higher (1 SD above the mean) or lower (1 SD below the mean) scores for oxytocin and testosterone reactivity, respectively (see Section 2.6). We note that we treated the hormone reactivity predictors as continuous variables in the models in Tables 3 and 4. OT, oxytocin; T, testosterone. *p*-values indicate statistically significant simple slopes analyses

4.1 | Fathers' oxytocin, testosterone, and post-partum parenting

In models predicting our two measures of post-partum parenting (direct care and play) and father-infant bonding, respectively, we found a consistent pattern wherein if fathers' oxytocin declined while holding their newborns then the relationship between testosterone reactivity and the parenting outcome was positive. Based on simple slopes analyses, fathers whose testosterone increased while first holding their newborns and who experienced greater concomitant decreases in oxytocin reported more involvement in direct caregiving and greater father-infant bonding months later, compared to men whose testosterone and oxytocin both declined during holding. Moreover, the effect sizes for these differences are likely to be socially meaningful for families and potentially developmentally impactful for infants. For illustrative purposes, based on the predicted values in Figure 2, fathers whose testosterone increased (+1 SD) and oxytocin declined (−1 SD) reported ~11.3% more direct caregiving, which is almost a full SD difference for direct care, compared to men whose testosterone and oxytocin declined (both −1 SD). Based also the predicted values in Figure 2, those two groups also differed for father-infant bonding scores by an effect size corresponding to ~0.7 SDs.

These patterns do not align with our predictions. They also contrast with relevant psychobiological frameworks in which higher oxytocin and lower testosterone are specifically proposed to relate to greater nurturing behavior and social bonding and the combination of increasing testosterone and decreasing oxytocin would likely correlate with lower parental involvement in direct care and nurturing play and less father-infant bonding (van Anders et al., 2011). For example, in studies on basal levels of these hormones, Gordon et al. (2017) found that Israeli fathers with higher oxytocin and lower testosterone engaged in more affectionate touch during observed interactions, and in a study of Congolese fisher-farmers, Gettler et al. (2019) showed that men with higher testosterone and lower oxytocin were rated as having more conflict with their wives. Moreover, there is increasing recognition that higher oxytocin can help focus attention towards socially salient contexts, regardless of whether they have positive or negative valence (Bartz et al., 2011; Crespi, 2016); for most fathers in this setting, their first interactions with their newborn would generally be characterized as highly socially salient. Thus, the role of fathers' decreasing oxytocin as a moderator of T's association with the post-partum outcomes is also surprising.

One possibility that merits mentioning is that the moderating effect of declining oxytocin could be an artifact of the study design, though we think this is unlikely to explain the observed results. Specifically, oxytocin's peripheral elimination half-life has been reported to be ~20 min (Leng & Ludwig, 2016). Given our study design included ~1 h between samples, it is plausible that for some men the second sampling time occurred during a trough of oxytocin production, in which the system was recovering from prior elevation. Unfortunately, we are not able to investigate this possibility. A second potential implication is that our reactivity results may challenge aspects of current conceptualizations regarding the roles of oxytocin and testosterone in parental psychobiology and other critical social and relational domains (Feldman,

TABLE 4 Robust regression models predicting post-partum father-infant bonding from interactions between their hormone reactivity change scores during newborn holding

Father-infant bonding	Oxytocin and testosterone reactivity								
	Model 1 (N = 98)			Model 2 (N = 98)			Model 3 (N = 98)		
	b	95% CI	p	b	95% CI	p	b	95% CI	p
Oxytocin	−0.01	(−0.03, 0.02)	.738	−0.002	(−0.03, 0.03)	.880	−0.01	(−0.04, 0.02)	.681
Testosterone	**0.08**	**(0.002, 0.17)**	**.044**	0.08	(−0.02, 0.18)	.122	0.05	(−0.05, 0.14)	.345
Oxytocin × testosterone	**−0.001**	**(−0.001, −0.00001)**	**.046**	−0.001	(−0.002, 0.00002)	.058	−0.0003	(−0.001, 0.0001)	.475
Fathers' age				−0.11	(−0.48, 0.27)	.577	0.14	(−0.24, 0.52)	.455
Fathers' direct caregiving							**0.20**	**(0.04, 0.35)**	**.014**
Fathers' play							**0.24**	**(0.04, 0.44)**	**.019**
Model R²	0.06			0.05			0.19		
AIC & BIC	AIC 76.60	BIC 89.94		AIC 67.49	BIC 84.25		AIC 99.74	BIC 120.25	

Note: All hormone variables (oxytocin, testosterone) refer to percentage change reactivity scores. Results in bold indicate statistically significant findings.

Abbreviations: AIC, Akaike information criterion; BIC, Bayesian information criterion.
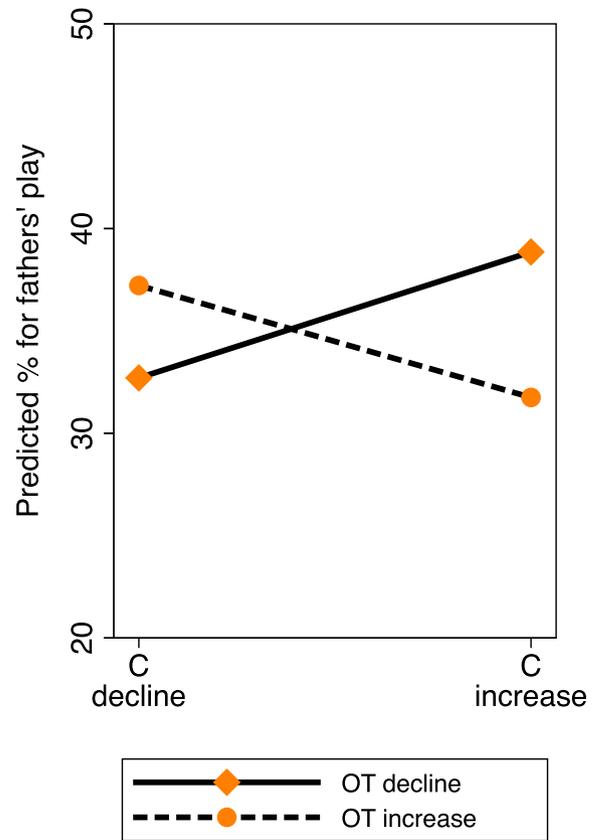
FIGURE 3 Men's post-partum direct caregiving, play, and father-infant bonding scores predicted from (oxytocin reactivity × cortisol reactivity). The plots were derived using predictive margins (adjusted predictions) following the Model 1 robust regression analyses in Table 3 for (oxytocin reactivity × cortisol reactivity). For visual purposes, we present predicted fathering outcomes based on fathers having relatively higher (1 SD above the mean) or lower (1 SD below the mean) scores for oxytocin and cortisol reactivity, respectively (see Section 2.6). We treated the hormone reactivity predictors as continuous variables in the models in Table 3, but also note that the simple slopes analyses for this interaction were not statistically significant (both p > .05; see Section 3). C, cortisol; OT, oxytocin

2012b; Gettler, 2014; van Anders et al., 2011). That being said, we are reluctant to speculate extensively in that vein and hope future research on fathers' hormone reactivity can test whether these patterns replicate.

We also found a main effect for testosterone reactivity in two model sets, such that fathers whose testosterone increased more during holding reported more direct caregiving and stronger father-infant bonding. This pattern for testosterone reactivity also ostensibly runs counter to predictions from relevant psychobiological framing (Gettler, 2014; van Anders, 2013; van Anders et al., 2011). However, fathers' testosterone has been shown to acutely increase in response to recorded infant cries and this has been interpreted as a potentially protective response (Fleming et al., 2002; Storey et al., 2000; see also Roellke et al., 2019; van Anders et al., 2012). Fathers' first holding of their newborns following the birthing process, which can be challenging, is likely to be a warm, nurturing experience for

many U.S. men (Johansson et al., 2012). Yet, it is also possible that some new fathers experience a strong protective feeling towards their vulnerable newborns during those early first interactions (Gloppestad, 1996), which may correlate with acute increases in testosterone as well as later involvement and bonding, though that is speculative.

In our models predicting father-child play, we also found a significant cross-over interaction for oxytocin and testosterone. Fathers whose testosterone decreased during initial father-child holding reported more play with their infants if their oxytocin also increased during holding. Based on the simple slopes analysis in Figure 2, men who experienced decreasing testosterone (−1 SD) and increasing oxytocin (+1 SD) played ~6.0% more than men whose testosterone and oxytocin both increased. They were also predicted to play ~8.6% more than fathers whose testosterone and oxytocin both declined. This pattern linking decreasing testosterone and increasing oxytocin to greater father-infant play more closely aligns with current conceptual frameworks and is particularly consistent with van Anders's proposal that warm, affectionate play (such as is likely with a small immobile infant) would be linked to this type of psychobiological function (van Anders, 2013; van Anders et al., 2011). These reactivity results for play also generally align with past work on Israeli fathers, which showed that fathers with higher basal oxytocin and lower testosterone engaged in more affectionate touch during play with their infants (Gordon et al., 2017).

4.2 | Fathers' oxytocin, cortisol, and post-partum parenting

We observed a cross-over interaction pattern for cortisol and oxytocin in predicting fathers' post-partum play, though the interaction term was not statistically significant nor were the simple slopes analyses. The moderating effects of oxytocin in this interaction shared some similarities to the patterns we found for (oxytocin × testosterone) in predicting play. For comparison, the effect sizes in Figure 3 for the simple slopes analyses reflect ~5.5%–6.0% difference in play, respectively, which corresponds to ~0.40–0.45 SDs for fathers' play. However, the confidence intervals were overlapping for the relevant simple slopes comparisons in Figure 3. Although we urge caution in over-emphasizing these analyses, we found results hinting that if fathers' oxytocin increased during holding there was a negative correlation between cortisol reactivity and play. That psychobiological pattern is potentially consistent with anxiety reduction, which, if repeated over time, could help facilitate nurturing and paternal involvement (Feldman, 2007). However, we note it is not clear why this would apply to father-infant play solely and not to direct caregiving as well. In our prior work from this study, we showed that fathers whose cortisol increased more during holding reported greater involvement in later play (Kuo et al., 2018). Our current findings provide further insights by indicating that if fathers' oxytocin decreased during holding there was a positive correlation between cortisol reactivity and play. As we noted in the Introduction, parents'

early post-partum cortisol has been linked to increased affection, sensitivity, and involvement in some research (Fleming et al., 1987; Kuo et al., 2018; Stallings et al., 2001). However, in the present study, it is unclear why a positive correlation between cortisol reactivity and play would be found for fathers with decreasing oxytocin, specifically.

4.3 | Fathers' oxytocin changes following first holding of their infants

We conducted this research in a UNICEF-recognized baby friendly hospital, which encourages an hour of immediate post-partum skin-to-skin contact between mothers and babies immediately after birth, if possible. There has been extensive research on the physiological effects of this immediate skin-to-skin contact on newborns' physiology (e.g., thermoregulation, oxygen saturation, heart rate), and it is specifically encouraged between mothers and babies to help facilitate breastfeeding (Boundy et al., 2016; Conde-Agudelo & Diaz-Rossello, 2016; Mori et al., 2010). Past research has found that both mothers' and fathers' oxytocin rose in response to skin-to-skin care with their newborns (Cong et al., 2015; Vittner et al., 2018). Here, we found that fathers' oxytocin was significantly higher following the first holding of their newborns, compared to their pre-holding levels. However, fathers' post-holding oxytocin following skin-to-skin contact was not significantly different than their pre-holding levels, whereas fathers who engaged in standard holding had higher oxytocin post-holding. The two groups did not differ significantly for percentage change in oxytocin during holding. First-time fathers specifically had elevated oxytocin post-holding, while pre- versus post-holding oxytocin levels did not differ significantly for experienced fathers. Recent work by Vittner et al. (2018) showed that parents with greater oxytocin increases during skin-to-skin care engaged in more sensitive and responsive care in the following days, aligning with broader research on oxytocin, sensitivity, and synchrony (Feldman & Bakermans-Kranenburg, 2017). Thus, encouraging fathers' early contact with their infants may (at least) have beneficial effects for families in the often exciting but also daunting first days of welcoming a newborn.

Finally, we found that experienced fathers had significantly higher oxytocin than first-time fathers prior to holding their newborns, though the two groups did not differ for percentage change in oxytocin. Prior psychobiological studies have documented inconsistent links between paternal experience and men's basal and reactivity hormone profiles. For example, fathers' basal testosterone did not significantly vary based on their number of children in studies in the U.S. and the Philippines (Gettler et al., 2015; Mascaro et al., 2014). However, in research focusing on fathers' hormone reactivity, experienced Canadian fathers showed greater cortisol and prolactin responses to recorded infant cries than first-time fathers (Fleming et al., 2002), while first-time Filipino fathers had larger short-term prolactin responses to father-toddler play (Gettler, McDade, Agustin et al., 2011). Past research specifically

testing for links between oxytocin and paternal experience have also produced mixed results. In two separate studies, Israeli and U.S. fathers' oxytocin did not significantly differ by experience (Feldman, Gordon, Schneiderman, et al., 2010; Mascaro et al., 2014). Elsewhere, Congolese Bondongo fathers tended to have higher oxytocin as their number of children increased (Gettler et al., 2019). In our study, it is possible that the oxytocinergic system was more activated or primed in experienced fathers, based on their prior parenting roles, than in first-time fathers, leading to increased output for experienced fathers in anticipation of holding their newborns. However, we also cannot rule out alternative explanations, such as the possibility that some experienced fathers interacted with their other children prior to first holding their newborns (e.g., while mothers engaged in skin-to-skin care in the first hour), leading to relatively higher oxytocin pre-holding.

4.4 | Limitations

There are limitations to the current study that merit discussion. The study would have been strengthened had the follow-up sample been closer in size to the original day-of-birth sample at the hospital. Greater sample size would have helped reduce the potential of Type II error and aided our interpretation for certain tests, such as (oxytocin reactivity × cortisol reactivity) in predicting father-infant play and bonding. Unfortunately, given funding limitations for the current project, we were only able to contact fathers and conduct our follow-up data collections remotely and had limited resources to engage in comprehensive retention strategies to minimize fathers' attrition at follow-up (Teague et al., 2018).

We also acknowledge that questions have been raised regarding measuring oxytocin in saliva. Studies conducted across a range of designs, including observational, experimental, and pharmacological research, help support the notion that salivary oxytocin is a useful index of peripheral oxytocin function (de Jong et al., 2015; Grewen et al., 2010; Martin et al., 2018; Weisman et al., 2012a). In studies comparing oxytocin across biological media, salivary oxytocin was a stronger indicator of cerebrospinal fluid oxytocin (i.e., levels in direct contact with the brain), relative to plasma oxytocin, which helps enhance our confidence in our measures (Martin et al., 2018). Finally, an additional limitation of the oxytocin data in the current analyses relates to the inter-assay CV for the control values, which are at or near the upper limit of what is often considered acceptable for this type of assay (ELISA). In general, this type of imprecision reduces the reliability of the data and thus should predispose our analyses to Type II error, rather than Type I error. However, we also emphasize that our analyses drew on within-individual changes in hormones, including oxytocin. Fathers' pre- and post-holding samples were analyzed on the same assay plates meaning that between-plate variability (i.e., as indicated by the inter-assay CVs) has minimal bearing on within-individual changes in oxytocin in the present study.

5 | CONCLUSIONS

Prior research on paternal psychobiology has found mixed evidence for relationships between fathers' acute hormone responses to father-child interaction and their routine involvement in childcare. Here, our results from a longitudinal research design are consistent with the general idea that fathers' psychobiology in the peripartum period may be attuned and primed to respond to their early interactions with their new infants and that this responsiveness is linked to their patterns of involvement and bonding in the subsequent postpartum months. However, many of the specific interaction patterns we observed (e.g., for oxytocin and testosterone) are inconsistent with predictions from relevant psychobiological frameworks and past research. Thus, we hope that these patterns will help to stimulate further research on the combinatorial relationships between parental hormones and family dynamics, which will help us expand our understanding of the complex and contextual expression of parental psychobiology, generally, and whether our results replicate, specifically.

CONFLICT OF INTEREST
The authors report no conflicts of interest.

AUTHOR CONTRIBUTION
LTG designed the study in consultation with JBR and JBL. LTG secured funding for the project. PXK and MSS assisted with data collection and cleaning and project management. MSS and BCT conducted laboratory work, and BCT provided expertise on assay-related components of the study. LTG wrote the article with input from the co-authors.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Lee T. Gettler https://orcid.org/0000-0001-7325-8852
Patty X. Kuo https://orcid.org/0000-0002-2185-4537
Mallika S. Sarma https://orcid.org/0000-0002-6693-9382
Benjamin C. Trumble https://orcid.org/0000-0003-3201-0628

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.