Foster Mother–Infant Bonding: Associations Between Foster Mothers' Oxytocin Production, Electrophysiological Brain Activity, Feelings of Commitment, and Caregiving Quality

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This study examined the biological processes associated with foster mother–infant bonding. In an examination of foster mother–infant dyads ($N = 41$, mean infant age = 8.5 months), foster mothers' oxytocin production was associated with their expressions of behavioral delight toward their foster infant and their average P3 response to images of all infant faces in the first 2 months of the relationship. Three months later, foster mothers' oxytocin production was still associated with delight toward their foster infant and was also specifically associated with their P3 response to an image of their foster infant. Similar to biologically related mothers and infants, oxytocin appears to be associated with foster mothers' brain activity and caregiving behavior, with patterns suggestive of bond formation.`

Oxytocin, a neuropeptide involved in social bonding, is associated with mother–infant relationship quality in both human and nonhuman mammals (Galbally, Lewis, van IJzendoorn, & Permezel, 2010; Kendrick, Keverne, & Baldwin, 1987; Neumann, 2008). Among biologically related mothers and infants, maternal peripheral oxytocin levels are associated with brain activity in response to infant stimuli (Strathearn, Fonagy, Amico, & Montague, 2009), maternal feelings (Feldman, Weller, Zagoory-Sharon, & Levine, 2007), and the quality of caregiving behavior (Gordon, Zagoory-Sharon, Leckman, & Feldman, 2010a, 2010b). However, it remains unclear whether oxytocin production has relevance for the formation and quality of nonbiological mother–infant bonds, such as those that occur in foster care. Given that foster infants are especially in need of high quality caregivers, investigating the biological correlates of alloparental bonding and caregiving behavior seems critical.

Oxytocin and Nonhuman Mammal Maternal Care

Oxytocin is a neuropeptide produced in the hypothalamus and is released centrally in the brain and peripherally into the bloodstream (Landgraf & Neumann, 2004). Centrally released oxytocin acts as a neurotransmitter or neuromodulator. When secreted into the peripheral blood system, oxytocin acts as a hormone and is best known for its role in facilitating uterine contractions during the birth process and milk ejection during nursing (Carter, 1998). The association between central and peripheral release of oxytocin is controversial and not fully understood. A minute amount of oxytocin ($< 1\%$) has been found to enter the brain from the bloodstream (Landgraf, Ermisch, & Hess, 1979; Mens, Witter, & van Wimersma-Greidanus, 1983), but it remains unclear whether this small amount leads to significant physiological changes (Ermisch et al., 1985). Several studies among humans and animals indicate that central and peripheral oxytocin release occurs independently (Neumann, 2007). However, additional studies suggest that the release of central and peripheral oxytocin can be

coordinated at times (Burri, Heinrichs, Schedlowski, & Kruger, 2008; Landgraf & Neumann, 2004; Wotjak et al., 1998).

Among several species of nonhuman mammals, oxytocin is necessary for the onset and expression of maternal behavior (Farbach, Morrell, & Pfaff, 1984; Kendrick et al., 1987; Pedersen & Prange, 1979; Van Leengoed, Kerker, & Swanson, 1987). Furthermore, a proliferation of oxytocin receptors in brain regions associated with maternal care has been associated with the quality of maternal behavior expressed toward offspring in several rodent species (Champagne, Diorio, Sharma, & Meaney, 2001; Insel, 1986; Pedersen, Vadlamudi, Boccia, & Amico, 2006).

Studies involving nonhuman mammals suggest that oxytocin plays a role in the expression of alloparental care. Among virgin juvenile female prairie voles, the number of oxytocin receptors in the brain has been associated with the quality of alloparental care exhibited toward vole pups (Olazábal & Young, 2006). Oxytocin receptor density has also been significantly linked with the quality of adult female rats' maternal behavior displayed toward biological and nonbiological cross-fostered young (Champagne et al., 2001).

Oxytocin and Human Mother–Infant Bonding

Given that the oxytocin system has been linked with parental behavior across numerous mammalian species, it is not surprising that oxytocin plays a role in bonding between human parents and infants. Plasma oxytocin levels during pregnancy have been correlated with mothers' feelings related to bonding to their infant (Levine, Zagoory-Sharon, Feldman, & Weller, 2007), attachment representations toward their infants, and maternal preoccupations regarding the health and safety of their babies (Feldman et al., 2007). Oxytocin has also been predictive of the quality of biological mothers' and fathers' behavior displayed toward their infants during parent–infant interactions (Feldman et al., 2007; Gordon et al., 2010a, 2010b).

There is some evidence to suggest that peripherally acting oxytocin is associated with brain activity in response to infant stimuli. Biological mothers' peripheral oxytocin levels have been linked with the activation of areas of the brain involved in the dopaminergic reward system (the ventral striatum and the nucleus accumbens; Atzil, Hendler, & Feldman, 2011; (Strathearn et al., 2009) and the oxytocin-associated hypothalamic and pituitary regions (Strathearn et al., 2009) when pre-

sented with stimuli involving their own infant. Although the exact mechanism linking central and peripheral activity is not known, several additional studies involving humans and animals have shown associations between peripheral oxytocin activity and central nervous system activity (Carson et al., 2010; Geenen, Adam, Baro, Mantanus, & Ansseau, 1988).

The Role of Oxytocin in Foster Mother–Infant Bonding

In the past decade, there have been exciting advances in the understanding of oxytocin's role in bond formation and caregiving quality among biological mothers and infants. However, to our knowledge, there have not been studies assessing the role of oxytocin in bond formation among non-biologically related dyads. Although there are numerous forms of naturally occurring alloparental relationships among humans, the current study focused on the development of foster mothers' relationships with their foster infants. Despite important differences between biologically related versus foster mothers (e.g., pregnancy and breast-feeding), it seemed plausible that oxytocin might also play a role in foster mothers' bonding with foster infants.

Oxytocin and Foster Mothers' Cognitions

Previous research has identified important psychological components of foster mother–infant relationships. The degree to which a foster parent feels committed to maintaining a long-term relationship with a foster infant appears to have important implications for foster infants' healthy behavioral and psychological adjustment (Dozier & Lindhiem, 2006; Lindhiem & Dozier, 2007). Relative to low levels of commitment, higher levels of commitment among foster mothers have been associated with reduced problematic behaviors among foster children (Dozier & Lindhiem, 2006).

Given prior evidence suggesting that oxytocin is associated with maternal bonding-related cognitions (Feldman et al., 2007; Levine et al., 2007), we hypothesized that foster mothers' oxytocin production would be positively associated with their feelings of commitment toward their foster infants. This seemed particularly important for understanding why foster mothers have been found to vary in the degree to which they report feelings of closeness and commitment to foster infants (Dozier & Lindhiem, 2006; Lindhiem & Dozier, 2007).

Oxytocin and Foster Mothers' Brain Activity

Recently, biological and foster mothers' brain activity in response to infant faces has been examined using event-related potentials (ERPs). ERPs are electrical potentials in the brain that are associated with physical or cognitive "events" and are extracted from the ongoing electroencephalogram (EEG) using signal-averaging techniques. The averaged ERP waveform consists of series of "components" often associated with overlapping positive (P) and negative (N) peaks normally referred to by polarity and latency.

A particularly well-studied component of the ERP, the P3 or P300, is a positive deflection occurring approximately 300 ms following a significant stimulus, and achieves its maximal amplitude at parietal recording sites. The P3 has been shown to increase when biological parents and foster parents view images of their "own" children versus unfamiliar children (Grasso, Moser, Dozier, & Simons, 2009; Weisman, Feldman, & Goldstein, 2012). In addition, biological and foster parents' P3 amplitudes in response to their "own" (biological or foster) children have been associated with the degree to which they are accepting of their children (by reporting pleasure, delight, and reward in their children) and feel that they are influential in their children's development (by valuing the nurturance they provide to their children; Grasso et al., 2009). Therefore, this ERP component seems to have particular relevance for foster mother–infant relationships.

Whether peripheral oxytocin is associated with electrophysiological brain activity in response to infant images has not yet been examined, to our knowledge. However, there is some evidence that peripheral oxytocin levels may be linked with ERP responses more generally. First, systemic administration of oxytocin into the blood stream has been associated with the activation of oxytocin receptor-rich areas of the brain among rodents. One activated area is the locus coeruleus, which is also considered to be a source of the P3 component among humans (Aston-Jones & Cohen, 2005; Carson et al., 2010; Tribollet, Dubois-Dauphin, Dreifuss, Barberis, & Jard, 1992). Second, there is evidence among humans that peripheral oxytocin levels are associated with ERP responses to the presentation of visual stimuli (Geenen et al., 1988). Taking the findings from prior research together, we hypothesized that foster mothers' oxytocin production would be positively associated with their P3 amplitudes in response to viewing infant images in the current study.

Oxytocin and Foster Mothers' Caregiving Quality

In previous research, behavioral delight has been identified as an important component of foster mothers' caregiving behavior (Bernard & Dozier, 2011). Foster mothers' behavioral delight, defined as displays of positive affect, smiling, praising, and active encouragement of mutual interaction that demonstrate a genuine affection and joy in playing with or being with one's child, has been associated with the degree to which foster mothers feel committed to their foster infants. Because parenting quality has been linked with peripheral oxytocin levels among biologically related parents and infants (Feldman et al., 2007; Gordon et al., 2010a, 2010b), we hypothesized that foster mothers who produced more oxytocin across a cuddle interaction with their foster infant would show greater displays of behavioral delight toward their infant during a play interaction.

The Current Study

As evident by the research to date, oxytocin appears to be an important biological correlate of maternal behavior, bonding-related cognitions, and brain activity in response to infant images. The current study examined whether foster mothers' oxytocin production was associated with their electrophysiological (ERP) brain activity in response to their foster infants, psychological variables that have been established as particularly relevant to caring for one's foster infant (i.e., their levels of commitment; Dozier & Lindhiem, 2006), and foster mothers' displays of delight, a behavioral variable that has been established as significant when caring for one's foster infant (Bernard & Dozier, 2011). We hypothesized that foster mothers' oxytocin production would be positively associated with their electrophysiological brain activity in response to images of their foster infants, reports of commitment, and expressions of behavioral delight at early and more established phases of the relationship.

Method

Participants

Forty-three foster mother–infant dyads participated in this study. At the start of the study, infants ranged in age from 0.5 months to 35 months old ($M = 8.5$, $SD = 9.6$). Fifty-five percent of the infants were females ($n = 24$). Twenty-five percent of the

foster infants were White or non-Hispanic, 35% were African American, and 40% were biracial. Foster mothers ranged in age from 28 to 68 years old ($M = 42.1$, $SD = 10.1$). Forty-seven percent of the foster mothers were White or non-Hispanic, 46% were African American, and 7% were Hispanic or Latino. Fourteen percent of the foster mothers had completed graduate school, 21% had completed college, 25% had completed some college, and 40% had completed high school. Forty-six percent of the foster mothers did not work, and 54% were employed either part time or full time. Seventy-nine percent of the foster mothers were married, 2% were living with a partner, 9% were divorced, and 10% were single. Twenty-four percent of the families had annual incomes > $100,000/year, 22% had incomes between $60,000 and $100,000/year, 29% had incomes between $40,000 and $60,000/year, 7% had incomes between $30,000 and $40,000/year, 10% between $20,000 and $40,000/year, and 8% had incomes below $20,000/year.

Procedure

After receiving consent from the foster mothers and infants, two laboratory visits ("A" and "B") were scheduled during the first 60 days of the foster infant placement (at this first visit, foster infants had lived with foster mothers for a minimum of .47 months to a maximum of 1.96 months, $M = 1.28$ months, $SD = .47$ months). At Visit A, foster mothers' oxytocin was measured after a cuddle interaction task with their foster. At Visit B, foster mothers' ERP brain activity in response to images of their foster infant, verbal reports of commitment, and behavioral delight (through a 10-min play interaction with their foster infant) were assessed. The order of these visits was counterbalanced between foster mothers. Foster mothers were asked to return to the lab to repeat Visits A and B, 3 months following the first visits. Due to scheduling issues, the timing of this visit ranged from 2.8 months to 6.6 months following the first laboratory visits ($M = 3.6$ months, $SD = .86$ months). At the second visit, infants had lived with their foster mothers for a minimum of 3.7 months to a maximum of 8.43 months ($M = 5.0$ months, $SD = 1.05$ months).

Measures

Composite risk variables. During the laboratory visits, foster mothers were asked to report on several parent and child risk variables found to be predictive of parent–child relationship quality and maternal behavior in previous research (Bakermans-Kranenburg, Breddels-van Baardewijk, Juffer, Velderman, & van IJzendoorn, 2008; Blair, 2002; Dozier & Lindhiem, 2006; Fisher, Burraston, & Pears, 2005; Lindhiem & Dozier, 2007; Schuler, Black, & Starr, 1995; Zeanah et al., 2001). Composites of multiple risk factors have proven more powerful in predicting problematic outcomes, when compared with examining individual risk variables in isolation (e.g., Sameroff, Seifer, Zax, & Barocas, 1987).

A child composite risk score was calculated by combining dichotomous scores for infant temperament, premature birth, previous number of foster placements, reports of prenatal drug exposures, evidence of physical or sexual abuse or neglect prior to the current foster placement, and child age. Foster infant temperament was assessed using the Infant Behavior Questionnaire and the Early Childhood Behavior Questionnaire (Gartstein & Rothbart, 2003; Rothbart, 1981). Infants with scores that fell 2 SD or more above the mean on the soothability subscale were coded as "high risk." Prematurity was determined if the infant either weighed < 2500 g at birth or was born at < 32 weeks gestation (or both), following guidelines in previous studies (Caputo et al., 1974; Minde, 1993). Two or more foster placements were coded as "high risk," as established in previous research (Lewis, Dozier, Ackerman, & Sepulveda-Kozakowski, 2007). Prenatal drug exposure and maltreatment history (defined as physical abuse, sexual abuse, or neglect) was assessed as present or absent. These variables have been associated with parenting quality in previous research (Bakermans-Kranenburg et al., 2008; Bustan & Sagi, 1984; Dozier & Lindhiem, 2006; van den Boom, 1994).

In previous research, foster infant age has been predictive of foster mothers' acceptance of and belief in the degree to which they could positively influence the infant in their care (Bates & Dozier, 2002) and foster mothers' commitment toward foster infants (Lindhiem & Dozier, 2007). In the current study, foster infant age was negatively associated with foster mothers' behavioral delight at the second laboratory visit (see online supporting information Appendix S3). For this reason, foster infant age was entered as a risk factor in the child composite variable. Child age was dichotomized based on the medium split and categorized as "high risk" if they were categorized as "older" (above the median) and "low risk" if categorized as "younger" (below the median). The total foster infant composite risk score ranged from 0 to 6, with higher scores reflecting the presence of more risk factors.

A composite score for foster mother risk was calculated by combining dichotomous measures of mental health status and number of previous foster children cared for, as these variables have been found to affect foster parents' commitment and delight (Dozier & Lindhiem, 2006). Foster mothers' mental health status was assessed through the Brief Symptoms Index, a 53-item self-report measure administered to assess the prevalence of psychological symptoms (Derogatis & Spencer, 1982). For the composite risk variable, scores that fell 2 *SD* or more above the mean on the global severity index of psychological health functioning were classified as "high risk." The previous number of foster children cared for was coded as "high risk" if the number of previous placements was 10 or more. The foster mother composite risk score ranged from 0 to 2, with higher scores reflecting more foster mother risk factors.

Foster mothers' oxytocin measurements. Oxytocin was measured through urine samples as part of a laboratory visit at the University of Delaware.

Foster mothers were encouraged to drink liquids before and during the visits to facilitate the process of voiding on three occasions. They were asked to avoid caffeine, nicotine, and alcohol before the laboratory visit as these substances can interfere with oxytocin production. All foster mothers reportedly complied with this request and no samples were excluded on this basis.

At the beginning of each lab visit, foster mothers and infants were separated from each other for 45 min so that oxytocin samples were not affected by physical contact apart from the experimental manipulation. Foster mothers were asked to sit in a room where they could not hear or see their foster infants. A staff member with extensive experience with infants cared for the foster infant in another room. After the first 20 min of this 45-min separation, foster mothers were asked to void in a private bathroom to rid their systems of oxytocin that may have accumulated peripherally prior to being separated from their infants. Oxytocin has been found to have a half-life of approximately 10 min and metabolic clearance rate of 1.4 L/min (Dawood, Ylikorkala, Trivedi, & Gupta, 1980). Therefore, it was expected that this time interval would allow for oxytocin levels to be sufficiently cleared from foster mothers' peripheral systems, and would allow for a valid estimation of baseline oxytocin levels.

At the end of the 45-min separation, foster mothers were asked to provide a preinteraction (baseline) urine sample. Following the collection of the sample, foster mothers were instructed to cuddle with their foster infants for 30 min. After the completion of this task, foster mothers were asked to provide the postinteraction urine samples as soon as they were able to do so. Given that oxytocin is secreted in a pulsatile fashion into the blood stream in as little as 5 min following physical contact (Turner, Altemus, Enos, Cooper, & McGuinness, 1999), this duration of 30 min was thought to be sufficient for measuring peripheral oxytocin production in response to cuddling. Pre- and postinteraction samples were then transferred to sterile cryogenic vials and stored in a freezer at −80°C until analyses by the Assay Services Unit. Urine samples were frozen for no longer than 6 months and were sent to the Wisconsin National Primate Research Center for assay.

Oxytocin assays. After controlled thawing, urinary samples were subjected to solid-phase extraction using 1 ml SepPak C18 cartridges (cat no. WAT023590; Waters, Milford, MA). Each column was pretreated with 1 ml of methanol and then 1 ml of water before application of 1 ml of urine. Samples were washed with 1 ml of 10% acetonitrile, 1% trifluroacetic acid. Oxytocin samples were eluted in 1 ml of 80/20% acetonitrile solution. Samples were then dried down in a water bath with air stream and reconstituted in the assay-appropriate buffer supplied in the 96-well ELISA assay kit used (cat no. 901-153; Assay Designs, Farmingdale, NY). Intra and inter coefficients of variation (CV) were determined by a human urine pool. Intra CV = 2.3 and Inter CV = 8.4. Oxytocin standards were used to determine recoveries from the extraction method and were 85%.

Oxytocin values. Oxytocin values that were more than 3 *SD* from the mean for each of the four data collection time points (pre- and postinteraction collections at Time 1 and Time 2) were considered outliers and were not included in the analyses. This excluded only mothers with high oxytocin values because the lowest possible value (0) was within 3 *SD* of the mean for each context. Three oxytocin values were identified as outliers across the four measurement points (one at the Time 1 preinteraction assessment, one at the Time 2 preinteraction assessment, and one at the Time 2 postinteraction assessment) and were therefore excluded from analyses.

The normality of the distributions of oxytocin values was also assessed. Due to the presence of significant skew, a square root transformation was employed to normalize the distributions for each time point. Total oxytocin production in response to the cuddle interaction was calculated by

subtracting the transformed preinteraction oxytocin values from the transformed postinteraction values at Time 1 and Time 2. Foster mothers' baseline oxytocin values (i.e., preinteraction oxytocin values) were marginally stable from Time 1 to Time 2, $r = .30$, $p = .09$. Foster mothers' oxytocin production during the cuddle interaction (i.e., the difference between postinteraction oxytocin values and preinteraction oxytocin values) was not stable from Time 1 to Time 2, $r = .10$, $p = .56$. Time elapsed between pre- and postinteraction measurements and time of day were not associated with foster mothers' oxytocin values and were therefore not included as covariates in subsequent analyses.

Foster mothers' P3 amplitude. The parietally maximal P3, previously associated with motivated attention to emotionally evocative stimuli and "loved ones" (Grasso et al., 2009; Langeslag, Jansma, Franken, & Van Strien, 2007; Vico, Guerra, Robles, Vila, & Anllo-Vento, 2010) was the ERP component of interest in the current study. Prior to a passive viewing task, foster mothers were familiarized with an image of a child they had not previously seen. The familiarization method was adapted from a prior study that examined the impact of familiar faces on ERP activity (Claypool, Hugenberg, Housley, & Mackie, 2007). Next, foster mothers participated in a passive viewing task. Foster mothers were presented with a series of faces in random order. For each foster mother, stimuli consisted of images of her foster child, the child to whom she was "familiarized," and an unfamiliar child. Familiar and unfamiliar faces were matched by age, gender, and facial expression to the foster mother's infant who participated in the study. Each face appeared on the computer screen for 2000 ms with an intertrial interval of 1500 ms using Presentation software (Neurobehavioral Systems Inc., Albany, CA). Pictures of the foster child, the familiar child, and the unfamiliar child were presented 25 times each in a pseudorandom order, for a total of 75 trials.

Data collection, processing, and analyses. ERP data were recorded from an electrode cap consisting of 32 Ag/AgCl electrodes. Placement of electrodes in the cap followed the International 10–20 System (Cooper, Osselton, & Shaw, 1969; Jasper, 1958). Advanced Neuro Technology Acquisition hardware (ANT, Enschede, the Netherlands) was used for EEG data collection with an average electrode reference and forehead ground. The continuous EEG was digitized at 512 samples per second and processed using advanced source analysis, a software package designed for ANT ERP systems. Re-referencing to the averaged mastoid was performed offline. The EEG was corrected for artifacts such as eye blinks and EKG (electrocardiogram artifacts), and bandpass filtered from 0.1 Hz to 30 Hz. EEG data that exceeded -75 μV or $+75$ μV were rejected. Average ERP waveforms, locked to picture onset, were computed for each condition (foster child, familiar child, or unfamiliar child) at each electrode. Averages were baseline corrected by subtracting the average voltage occurring during the 200 ms before the presentation of the infant image from the entire average. The P3 component was defined as the average amplitude within time windows of 300–650 ms following stimulus presentation. For these analyses, the Pz electrode was examined, as the P3 component associated with motivated attention has been found to be maximal at this electrode site (Schupp et al., 2004).

ERP P3 values. Prior to analyses, the validity of ERP data was examined for each participant at Time 1 and Time 2. After the processing of ERP data, two participants at Time 1 had fewer than 15 trials in the "foster child" condition due to excessive noise that occurred during data collection. Therefore, the ERP data for these participants were excluded from analyses. In addition, one foster mother did not complete the ERP portion of the laboratory visits at Time 1 because her child left her care. There were no missing data for ERP activity at Time 2.

Differences between foster mothers' P3 responses to pictures of their foster infants and to pictures of familiar and unfamiliar infants were explored at Time 1 and Time 2 (see Table 1 for descriptive statistics). At Time 1 and Time 2, results of separate repeated measures analyses of variance (ANOVAs) revealed a significant effect of stimulus type (i.e., foster, familiar, or unfamiliar) on P3 amplitude at Time 1, $F(2, 78) = 9.22$, $p < .001$, and Time 2, $F(2, 64) = 9.89$, $p < .01$ (see online supporting information Appendix S1). Post hoc comparisons revealed that the foster mothers' P3 responses to their foster infants were significantly larger than their P3 to the familiar and unfamiliar infants at Time 1 and Time 2 (p values $< .01$). Foster mothers' P3 responses to the familiar infants did not differ significantly from their P3 responses to the unfamiliar infants at Time 1 or Time 2 (see Figure 1).

For the primary analyses, we were interested in examining foster mothers' P3 responses to their foster infants when controlling for their P3 responses to the familiar and unfamiliar infant faces. Therefore, we calculated a difference score by subtracting the average of each foster mother's P3 response to the familiar and unfamiliar infant faces from her P3

Table 1

Ranges, Means, and Standard Deviations of Oxytocin, P3 Amplitudes, Delight, and Commitment at Time 1 and Time 2

	Min.	Max.	*M*	*SD*
Time 1 variables				
T1 oxytocin production (*N* = 42)	−8.09	6.58	0.89	3.71
T1 P3 "unique" foster amplitude (difference score; *N* = 40)	−1.12	2.34	0.53	0.89
T1 P3 average amplitude to all infants (*N* = 40)	0.24	4.23	1.96	0.97
T1 foster mother delight (*N* = 41)	1.00	5.00	3.95	1.07
T1 foster mother commitment (*N* = 39)	1.00	5.00	3.45	0.70
Time 2 variables				
T2 oxytocin production (*N* = 32)	−5.01	10.32	1.22	3.24
T2 P3 "unique" foster amplitude (difference score; *N* = 33)	−1.80	2.47	0.64	1.01
T2 P3 average amplitude to all infants (*N* = 33)	0.42	4.99	2.14	0.94
T2 foster mother delight (*N* = 33)	1.00	5.00	4.07	1.19
T2 foster mother commitment (*N* = 33)	2.00	5.00	4.18	0.76

response to her foster infant's face. For the sake of clarity, we will refer to this difference score as foster mothers' "unique P3 amplitude to their foster infant" for the remainder of this article. We were also interested in examining foster mothers' average P3 responses to all infant faces, regardless of familiarity. Therefore, we averaged each foster mother's P3 amplitude to the foster, unfamiliar, and familiar conditions. Hereinafter, we will refer to this variable as foster mothers' "average P3 amplitude to all infant faces." The difference score and average score were both used as variables in primary analyses.

In the current study, foster mothers' P3 amplitude to one's foster infant, $r = .52$, $p < .01$; the familiar infant face, $r = .54$, $p < .01$; and the unfamiliar infant face, $r = .57$, $p < .01$, remained highly stable over time. Foster mothers' average P3 amplitudes to all infant faces also remained highly stable over time, $r = .71$, $p < .001$. However, foster mothers' unique P3 amplitudes to their foster infants (i.e., the difference between foster mothers' P3 to their own foster infant minus their average P3 to an unfamiliar and familiarized infant) did not remain stable from Time 1 to Time 2, $r = .07$, $p = .70$.

Foster mother commitment. Foster mother commitment was assessed using the "This Is My Baby" (TIMB) interview developed by Bates and Dozier (1998). The TIMB interview is a semistructured interview, in which foster parents are asked about
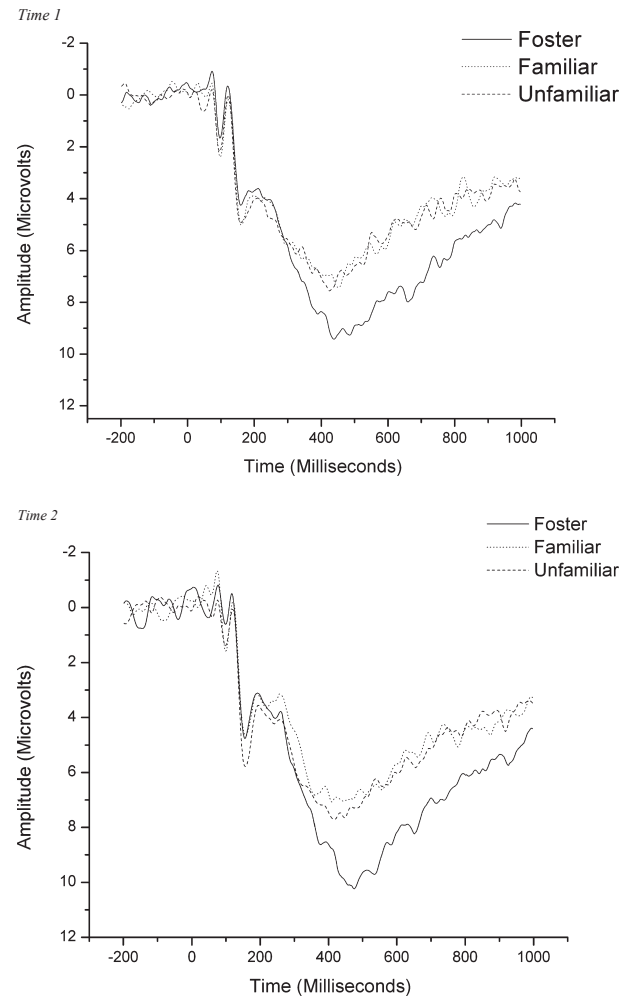

Figure 1. Foster mothers' P3 amplitude to foster, unfamiliar, and familiar images: Time 1 and Time 2.
Note. Please note that the convention is to plot event-related potential waveforms with negative voltages upward and positive voltages downward.

their long-term goals for the foster child, how much influence they feel they have in shaping the child's long-term development, and how much they would miss the child if he or she left their care. Interviews were transcribed and coded by two independent coders. Commitment is rated on a 5-point Likert scale. Prior research has provided evidence of the TIMB's predictive validity and test–retest reliability (Bernard & Dozier, 2011; Dozier & Lindhiem, 2006; Lindhiem & Dozier, 2007). Good interrater reliability has been established for this measure in prior studies and in the current study, intraclass correlation (ICC) = .82, $p < .001$.

At Time 1, commitment data were missing for 4 participants (2 participants' foster infants were removed from their foster placements prior to the

measurement of commitment and 2 participants' data were not able to be coded due to audio-recorder problems). There were no missing data for commitment at Time 2 among the remaining 33 participants. In the current study, foster mothers' commitment scores were moderately stable from Time 1 to Time 2, $r = .47$, $p < .01$.

Foster mother delight. Foster mothers' behavioral expressions of delight were assessed by coding foster mothers' behavior during a 10-min play interaction with their foster infants. Foster mothers were asked to participate in a standardized play interaction. Foster infants were seated in an infant seat and foster mothers sat directly in front of them. Foster mothers and infants were provided with a set of standardized toys. If the foster infant was < 20 months of age, a rattle, a set of cups, and soft toy were provided. If the foster infant was 20 months or older, a set of blocks was provided. Foster mothers were asked to play with their foster infants "as they typically would" for 10 min. The interaction was videotaped from behind a two-way mirror.

Displays of delight toward their foster infant were coded from the videotaped play interactions. Delight was rated on a 5-point Likert scale. Examples of high ratings of delight included displays of genuine affection, physical closeness, and obvious joy when interacting with the child. Low ratings were assigned to foster mothers who interacted with their foster infants without affective involvement or who appeared uninterested in interacting with their foster infants. This measure, which was adapted from the Maternal Delight Scale used by Ainsworth et al. (1978), has been shown to have concurrent validity and good interrater reliability (Bernard & Dozier, 2011). Interrater reliability in the present study was good (ICC = .84, $p < .001$). At Time 1, behavioral delight data were missing for 2 participants (2 participants' foster infants were removed from their foster placements prior to the measurement of behavioral delight). There were no missing data for behavioral delight scores at Time 2 among the remaining 33 participants. Foster mothers' displays of behavioral delight were moderately stable from the first to second laboratory assessment ($r = .41$, $p < .05$).

Results

Preliminary Analyses

The current sample consisted of 43 foster mother–infant dyads at Time 1. However, only 41 foster mothers were included in primary analyses due to the exclusion of one foster mother with outlying oxytocin data and one foster mother with both outlying oxytocin and P3 data (reasons for missing data are described in Method section). Ten of the 43 foster mothers and infants did not return for the Time 2 visit because the foster infants had left their care. Therefore, the Time 2 sample consisted of 33 foster mothers and infants. However, only 32 foster mothers were included in primary analyses due to the exclusion of one foster mother with outlying oxytocin values at Time 2. There were no significant differences in foster mothers' oxytocin production, $F(1, 41) = .706$, $p = .41$; delight, $F(1, 42) = .448$, $p = .51$; unique P3 amplitude to their foster infant, $F(1, 39) = .489$, $p = .49$; average P3 amplitude to all infant images, $F(1, 39) = .585$, $p = .45$; and commitment, $F(1, 38) = 1.91$, $p = .17$, between mothers who did and did not return to follow-up assessments at Time 2. Given the small sample size, mean imputation was performed on missing values of foster mothers delight (2 foster mothers at Time 1), commitment (4 foster mothers at Time 1), and P3 activity (1 foster mother at Time 1) to conserve power in primary analyses.

Descriptive characteristics at Time 1 and Time 2 for foster mother commitment, delight, oxytocin production during the cuddle interaction, and P3 amplitude are presented in Table 1. Correlations between primary variables of interest (foster mothers' commitment, delight, oxytocin production during the cuddle interaction, unique P3 amplitude to their foster infant, and average P3 amplitude to all infants) and demographic characteristics are presented in online supporting information Appendices S2 and S3. Because caregiver age, education, marital status, and income were not significantly associated with the primary variables of interest, these variables were not included as covariates in primary analyses (see online supporting information Appendices S2 and S3). There were no significant associations between placement length and variables of interest; therefore, placement length was not entered as a covariate in primary analyses at Time 1 or Time 2. Finally, we explored whether the range of time elapsed between assessment visits was associated with the primary variables of interest. The amount of time between Time 1 and Time 2 assessments ranged from 2.79 months to 6.64 months ($M = 3.6$, $SD = .86$). However, this variability was not significantly associated with foster mothers' change in oxytocin production during the cuddle interaction, $r = .23$, $p = .24$, at Time 2. Therefore, time elapsed between the first and

second laboratory visits was not included as a covariate in analyses.

Oxytocin Production Across the Cuddle Interaction

A series of separate repeated measures ANOVAs were conducted to examine patterns of oxytocin production across the cuddle interaction at Time 1 and Time 2. Foster mothers' oxytocin levels were not significantly different at postinteraction assessments when compared to preinteraction assessments at Time 1, $F(1, 42) = .85$, $p = .36$, or Time 2, $F(1, 31) = 2.20$, $p = .15$. Consistent with previous research (Feldman, Gordon, Schneiderman, Weisman, & Zagoory-Sharon, 2010), foster mothers varied in whether their oxytocin increased across the cuddle interaction (see Table 1 for descriptive statistics). We also examined whether foster mothers' oxytocin production varied from the first to the second laboratory assessment. Results from a repeated measures ANOVA revealed that foster mothers' oxytocin production across the cuddle interaction at Time 1 was not significantly different from their oxytocin production at Time 2, $F(1, 30) = .01$, $p = .95$.

Associations Between Oxytocin Production and Delight, Commitment, and Brain Activity

Associations between foster mothers' oxytocin production across the cuddle interaction and foster mothers' average P3 amplitude to all infant images, unique P3 amplitude to their foster infant, commitment, and behavioral delight were examined using multiple regression. Two separate multiple regression models were computed for Time 1 and Time 2 data.

At Time 1, foster mothers' oxytocin production across the cuddle interaction was regressed on their average P3 to all infants, unique P3 amplitude to their foster infant, commitment, and delight. Caregiver and child composite risk variables were also included in the model as covariates. The overall model at Time 1 was statistically significant, $F(6, 40) = 2.37$, $p = .05$, and accounted for 29.5% of the variance in foster mothers' oxytocin production across the cuddle interaction (see Table 2). A post hoc power analysis was conducted for $R^2 = .295$. Power was found to be .83 with six predictors in the model, for $N = 41$, $p = .05$.

A second regression analysis was performed for the Time 2 data. Foster mothers' oxytocin production across the cuddle interaction at Time 2 was regressed on their average P3 amplitude to all

Table 2

Time 1 and Time 2 Linear Regression for Oxytocin Production Across the Cuddle Interaction

	B	SE	β	Est./SE	p value
T1 oxytocin regressed on					
T1 delight	1.55	0.54	0.43	2.86	.007**
T1 commitment	−0.99	0.63	−0.25	−1.58	.124
T1 P3 to foster	−0.49	0.65	−0.12	−0.76	.453
T1 P3 average	1.32	0.60	0.34	2.21	.034*
T1 foster parent composite risk	0.32	0.58	0.08	0.56	.582
T1 foster infant composite risk	1.65	1.03	0.24	1.61	.117
(Constant)	−5.18	3.12	—	−1.67	.105
T2 oxytocin regressed on					
T2 delight	1.03	0.44	0.38	2.33	.028*
T2 commitment	0.16	0.65	0.04	0.25	.803
T2 P3 to foster	1.10	0.48	0.35	2.30	.030*
T2 P3 average	0.08	0.54	0.02	0.14	.889
T2 foster parent composite risk	1.13	0.83	0.21	1.37	.182
T2 foster infant composite risk	1.05	0.56	0.31	1.87	.073
(Constant)	−0.56	3.30	—	−1.77	.090

Note. T1 adjusted $R^2 = .17$, T2 adjusted $R^2 = .33$.
*$p < .05$. **$p < .01$.

infants, unique P3 amplitude to their foster infant, commitment, and delight collected at Time 2. Similar to Time 1 analyses, caregiver and child composite risk variables were also included in the model as covariates. The overall model at Time 2 was statistically significant, $F(6, 31) = 3.53$, $p < .05$, and accounted for 45.9% of the variance in foster mothers' oxytocin production across the cuddle interaction (see Table 2). A post hoc power analysis was also conducted for $R^2 = .459$. Power was found to be .96 with six predictors in the model, for $N = 32$, $p = .05$.

Associations Between Oxytocin and Foster Mothers' Bonding Variables: Is Oxytocin Production Associated With Foster Mother Delight and Commitment?

At Time 1, foster mothers' total oxytocin production in response to the cuddle interaction was significantly associated with the amount of behavioral delight exhibited during a play interaction, when controlling for foster parent and infant composite risk factors ($β = .43$, $p < .05$; see Table 2). At Time 2, foster mothers' total oxytocin production in response to the cuddle interaction continued to be associated with foster mothers' displays of behav-

ioral delight toward their foster infants, when controlling for foster parent and infant risk variables ($\beta = .38$, $p < .05$; see Table 2). Foster mothers who produced more oxytocin while cuddling with their foster infants displayed higher levels of behavioral delight during a play interaction with their infant. This association was observed at the first assessment, which occurred in the first 2 months of the foster mother–infant relationship, and at an assessment that occurred 3 months later.

Foster mothers' total oxytocin production was not associated with levels of commitment at Time 1 ($\beta = -.25$, $p = .12$; see Table 2). Similar to Time 1, foster mothers' total oxytocin production in response to the cuddle interaction was not significantly associated with reports of commitment at Time 2 ($\beta = .04$, $p = .80$; see Table 2).

Is Oxytocin Production Associated With Foster Mother P3 Activity?

At Time 1, foster mothers' total oxytocin production in response to the cuddle interaction was significantly associated with the amplitude of their average P3 to all infant faces ($\beta = .34$, $p < .05$), but was not significantly associated with the unique P3 amplitude to their foster infant ($\beta = -.115$, $p = .45$; see Table 2). Foster mothers who showed greater increases in oxytocin after cuddling with their foster infants showed larger P3 components in response to viewing all babies' pictures. At Time 1, foster mothers' oxytocin production was not related to the unique P3 amplitude to their foster infant.

At Time 2, foster mothers' total oxytocin production in response to the cuddle interaction with their foster infants was no longer associated with their average P3 amplitude to all infants ($\beta = .02$, $p = .89$); however, foster mothers' total oxytocin production was now significantly associated with the amplitude of the unique P3 amplitude to their foster infants ($\beta = .35$, $p < .05$; see Table 2). At this later assessment, foster mothers who produced more oxytocin after cuddling with their foster infants showed larger unique P3 amplitudes to their foster infant, when compared to foster mothers who produced less oxytocin. Unlike Time 1, oxytocin was no longer associated with foster mothers' average P3 amplitude to all babies.

Discussion

Oxytocin has been studied extensively among biologically related parent–infant dyads and has been associated with maternal caregiving behavior, attachment-related thoughts, and brain activity in response to infant stimuli. Although foster parents do not experience the physical conditions of childbirth and lactation known to affect oxytocin production, previous research on maternal caregiving among humans and animals suggests that oxytocin may play an important role in bond formation toward nonbiological infants. Our results are exciting in showing that even when biological relatedness is eliminated as a factor (and issues of pregnancy and breastfeeding are eliminated), oxytocin may still relate to bond formation in meaningful ways. Specifically, individual differences in foster mothers' oxytocin levels are associated with the amount of behavioral delight exhibited toward one's foster infant and the pattern of brain activity that emerges in response to viewing infant images.

Results from this study revealed that oxytocin, a neurohormone associated with affiliative behavior, was associated with foster mothers' brain activation in response to infant stimuli and with the quality of maternal behavior, with the pattern of associations changing over time. First, foster mothers' oxytocin levels were associated with their electrophysiological brain activity in response to infant stimuli. Interestingly, the manner in which foster mothers' oxytocin production was associated with their brain activity changed over the course of the foster mother–infant bond. In the first 2 months of the relationship, foster mothers' oxytocin production in response to a cuddle interaction was associated with their brain activity in response to infants in general, but not to the specific brain activity elicited in response to their "own" foster infant. However, over time, foster mothers' oxytocin production in response to a cuddle interaction became significantly linked to their brain activity in response to viewing their "own" foster infant. These associations over the first months of the foster mother–infant relationship may depict the biological processes that are associated with foster mothers' bond formation with nonbiological children.

Furthermore, foster mothers' oxytocin production in response to a cuddle interaction was significantly associated with their behavioral expressions of delight toward their foster infants in a play interaction. The association between foster mothers' oxytocin production and behavioral delight emerged during the first 2 months of the foster mother–infant relationship and at a follow-up assessment that occurred 3 months later. Whereas foster mothers' oxytocin production in response to a cuddle interac-

tion was not found to be stable over time when examined independently, its association with foster mothers' behavior (when controlling for composite foster parent and child risk factors) appeared to persist over time, at least through the initial phase of the foster mother–infant relationship.

Associations between oxytocin systems and alloparental behavior have been demonstrated in studies involving nonhuman mammals (Olazábal & Young, 2006). The animal literature has focused on associations between oxytocin receptor density and alloparental caregiving quality (Champagne et al., 2001; Olazábal & Young, 2006), but such associations have not yet been demonstrated among humans, to our knowledge. Even less is known about peripheral oxytocin activity and alloparental caregiving in human or animal species. The findings from the current study therefore contribute to the literature in suggesting that neurohormonal mechanisms related to peripheral oxytocin production are involved in nonbiological parenting among humans.

At the first assessment (which occurred in the first 2 months of the foster parent–infant relationship), foster mothers' oxytocin production in response to a cuddle interaction was associated with their average P3 amplitude to all infants. Therefore, foster mothers who produced more oxytocin in response to cuddling with their infant were also more likely to show a greater P3 response when presented with infant stimuli relative to foster mothers who produced less oxytocin during a cuddle interaction. The convergence in foster mothers' oxytocin production and average P3 amplitude to all infant faces may illustrate individual differences in the degree to which foster mothers respond to infant stimuli. This convergence early on in the foster mother–infant relationship may reflect the degree to which foster mothers find infant stimuli rewarding and may indicate their potential for providing high quality alloparental care. Although it is not possible to infer the direction of association (given the cross-sectional nature of the association), it is interesting to consider the mechanism that may explain the association between these variables. It is possible that foster mothers' greater P3 amplitude, or motivated attention, to all infant faces leads them to produce more oxytocin when cuddling with an infant, even when the relationship is relatively new. However, given previous research indicating the effects of synthetic oxytocin on nonparents' brain activity in response to hearing unfamiliar infants' cries or laughter (Riem et al., 2011, 2012), it is equally possible that foster mothers'

higher levels of oxytocin production in response to cuddling may cause increased motivated attention to infant-related stimuli.

Interestingly, the nature by which foster mothers' oxytocin production was associated with their brain activity changed over time. At the follow-up assessment, which occurred approximately 3 months following the initial assessment, foster mothers' oxytocin production in response to a cuddle interaction was no longer associated with their average P3 amplitude in response to all infant images. However, unlike the initial assessment, foster mothers' oxytocin production in response to a cuddle interaction at the follow-up assessment was associated with the magnitude of their unique P3 amplitude in response to their own foster infants. Therefore, foster mothers' oxytocin production became linked specifically with their unique P3 amplitude to their foster infant over time. When visually examining the strength of the associations, it appeared that the magnitude of the associations between foster mothers' oxytocin production in response to a cuddle interaction and average P3 activity to all infants decreased over the course of the relationship. In contrast, the associations between foster mothers' oxytocin production and unique P3 amplitude to one's own infant appeared to increase over the course of the relationship.

When interpreting these findings, it is important to consider the biological systems that may be associated with the coactivation of foster mothers' oxytocin production and P3 responses to infant stimuli. Both P3 amplitudes and peripheral oxytocin levels have been linked to the activation of the dopaminergic reward system. The P3 component has been hypothesized as at least partially reflective of activation of the locus coeruleus, which receives input from limbic areas via projections from dopaminergic reward systems in the brain, and projects to cortical areas involved in increased attention to motivational and emotional stimuli (Aston-Jones & Cohen, 2005). In two recent studies, peripheral oxytocin release during mothers' play interactions with their biological infants was associated with activation of reward regions in the brain (Atzil et al., 2011; Strathearn et al., 2009). Therefore, the association between foster mothers' oxytocin and average P3 amplitude to all infant faces early on in the relationship may signify an activation of foster mothers' reward system in response to all infant stimuli, possibly signaling individual differences in foster parents' capabilities for exhibiting high-quality alloparental care. The associations between foster mothers' oxytocin production and specific P3 activ-

ity to their foster infant, observed later on in the relationship, may reflect changes in the degree to which their specific foster infant becomes motivating or rewarding. Therefore, P3 activity and oxytocin may be influenced by the activation of the dopaminergic reward system in response to general infant stimuli in the early stages of the mother–infant relationship and specific stimuli related to their own foster infant after the relationship becomes more established.

There are limitations that should be kept in mind when interpreting the results of this study. Several human and animal studies have indicated that urinary concentrations of oxytocin are connected with social behavior and bonding (Seltzer & Ziegler, 2007; Seltzer, Ziegler, & Pollak, 2010). However, it is currently unclear how oxytocin levels in urine are related with levels of oxytocin in other peripheral systems such as blood and saliva (Feldman, Gordon, & Zagoory-Sharon, 2011). Therefore, we cannot conclude, based on the results of this study, that all peripheral levels of oxytocin are equally associated with foster mothers' brain activity and behavior in response to their foster infants. Second, due to the small sample size, it is likely that many of our analyses were underpowered to detect statistically significant differences. The small sample size, especially at Time 2, also limits the replicability of these findings. Therefore, the results from this study should be interpreted with caution. Third, although the results from the current study suggest that peripheral oxytocin is associated with bonding among nonbiologically related foster mothers and infants, it is equally possible that these patterns would be observed during the bonding process among biological mothers and infants, or even among adults who interact with unfamiliar infants. In fact, in previous research, we have found that adult female mothers produce oxytocin even when participating in a close cuddle interaction with an unfamiliar child (Bick & Dozier, 2010). To understand the unique manner in which oxytocin is associated with alloparental care in human relationships (such as those that occur in foster care), future research should include comparison groups of biologically related mother–infant and unfamiliar women–infant dyads.

Fourth, we interpreted foster mothers' increased P3 activity in response to their own foster infants as reflective of their increased "motivated attention" to their own children. Although we found foster mothers' unique P3 amplitude to the image of their foster infants to be greater than the P3 activity to a familiar face, we cannot rule out the possibility that

the increased activity to one's own foster child was merely due to an increase in the foster parents' familiarity with their foster infants' face. Future studies might improve upon this method by examining foster parents' P3 amplitude in response to a familiar child's face that is not cared for by the foster parent in combination with stimuli used in the current study.

Finally, the results from this study generalize to a sample of foster mothers and infants who remain together for approximately 6 months or less. However, it remains unclear whether the associations observed in the current study might generalize to a population of foster mothers and infants whose relationships last for shorter or longer periods of time. Given that numerous studies have suggested that oxytocin plays a significant role in the expression of parental behavior among fathers (Feldman et al., 2010; Gordon et al., 2010a, 2010b; Naber, van IJzendoorn, Deschamps, van Engeland, & Bakermans-Kranenburg, 2010), it also seems important to assess whether these results generalize to foster parenting among father–infant dyads. Furthermore, infants are a subset of the total number of children who are cared for by foster parents; it would be interesting to examine whether these findings extend to a population of foster parents caring for older children.

Despite these limitations, the results from the current study provide information on the biological variables that are associated with the expression of high quality parenting behavior toward nonbiologically related infants. This study suggests that biological systems may be associated with the development of a maternal attachment to foster infants. This has important clinical implications for populations of nonbiologically related and biologically related parents and infants. In summary, we believe that these results not only help us understand why individuals vary in the quality of caregiving provided to a specialized group of at-risk infants but also may aid in the development of interventions designed to promote healthy parent–infant relationships more broadly.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Average Amplitude of P3 Response to Foster, Familiar, and Unfamiliar Images (μV).

Appendix S2. Time 1 Correlations Between Bonding Variables and Demographic Characteristics.

Appendix S3. Time 2 Correlations Between Bonding Variables and Demographic Characteristics.