Oxytocin: An Evolutionary Framework

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Abstract and Keywords

Substantial excitement surrounds the mammalian peptide hormone oxytocin (OT) due to its potential to be a “hormone of love”—and more generally, a biological foundation for the diverse classes of intimate social bonds. Yet, theoretical models have struggled to absorb inconsistent, even contradictory, findings. Evolutionary theory will guide a coherent functional interpretation of the OT system. This chapter focuses on life history theory, a branch of theoretical biology that seeks to identify how natural selection shapes organisms’ efforts to optimally allocate limited resources. Endocrine hormones are important mediators of this process. A review of the psychological and physiological literature regarding OT suggests a number of possible trade-offs negotiated by oxytocinergic activity. This chapter proposes a provisional life history model in which OT is central to the regulation of important but vulnerable social relationships. It outlines implications of this model, addresses a number of caveats, and suggests directions for future research.

Keywords: oxytocin, life history theory, trade-offs, behavioral endocrinology, evolutionary biology

Evolutionary psychologists, in the tradition of Tinbergen’s (1963) “four questions,” are interested in the physiological underpinnings of psychological mechanisms. Hormones have become a point of focus as theoretically powerful tools for building a conceptually coherent evolutionary framework linking physiology to behavior. Life history theory, a branch of theoretical biology, identifies hormones as components of a system that evolved to solve contingent allocation problems—that is, they are solutions to demands that organisms adaptively allocate energetic and other resources differently depending on conditions, as assessed by cues external or internal to the organism (e.g., Finch & Rose, 1995). Though some hormonal systems have been analyzed in this manner (e.g., Bribiescas, 2001; Ellison, 2003), oxytocin (OT) has not. Here, we advance a conceptualization of the OT system derived from life history theory, as a demonstration of the significance this approach has for evolutionary behavioral endocrinologists.

OT is a mammalian protein hormone. It evolved within a larger family of structurally similar "-tocin" peptides (e.g., vasotocin, mesotocin) that is observed in birds, reptiles, and invertebrates, which likely debuted 600+ million years ago (Gruber, 2014). OT is well known within medical circles for its functions in parturition and lactation, and it has well-established effects on maternal behavior (e.g., Numan, 2017). Since the discovery that OT may also be crucial to the formation of sexual pair-bonds in certain species (e.g., Williams, Insel, Harbaugh, & Carter, 1994) in ways similar to how it affects mother–offspring bonds (Nelson & Panksepp, 1998), scientists and laypeople alike have been fascinated by the possibility that this biological messenger is integral to the most meaningful, "close," social relationships in our lives. Indeed, the hormone has been labeled, variously, as the "love," "cuddle," or "trust" hormone (e.g., Uvnäs-Moberg, 2003; Zak, 2012). About 15 years ago, means of experimentally administering OT via nasal spray were developed, and today over (p. 318) 500 experimental administration studies of OT can be found in the literature. Contrary to some initial expectations, OT does not uniformly promote prosocial behavior and feelings of warmth. Mixed findings have led to a proliferation of attempts to conceptualize OT's many and contrasting effects within a single, coherent framework (see, e.g., Bethlehem, Baron-Cohen, van Honk, Auyeung, & Bos, 2014; Churchland & Winkielman, 2012; Crespi, 2016; Numan & Young, 2016). New perspectives continue to appear and evolve (e.g., Hurlemann & Scheele, 2016), and no consensually agreed-upon resolution has been reached.

We review the major conceptual frameworks for understanding OT, but, more fundamentally, we step back and try to view OT and its manifestations with a wider lens. The OT system is an evolved one. Though this system has a range of psychological effects, it also controls physiological outcomes that are nonpsychological in nature via effects on a wide array of bodily tissues. Psychological and nonpsychological manifestations of the OT system likely have effects coordinated to serve its functions. Hence, a full, coherent explanation of the functions of the OT system should also account for OT's nonpsychological effects. In early mammalian species, these functions likely regulated particular relationships, notably the mother–offspring one; only more recently did it acquire functions that promote other relationships. A broader, evolutionary view suggests the OT system coordinates a host of effects, which likely evolved initially in the context of certain relationships —this, we feel, guides a coherent interpretation. In addition to reviewing the major psychological conceptualizations put forward to date, we develop and emphasize the argument for this framework.

Our chapter has four sections. First, we start with some foundational notions—specifically, a broad life history framework for understanding the evolved functions of endocrine hormones. This framework offers reasons that, when seeking to explain the function of any particular hormonal effect, other effects are pertinent. It also integrates phylogenetic perspectives that pertain to how endocrine systems evolve.

Second, we give an overview of the literature on OT's psychological effects. We begin with well-established neuromodulatory effects in nonhuman mammals and end with a special focus on humans.

Third, we attempt to place OT's neuromodulatory effects in the broader evolutionary framework emphasizing hormonal modulation of resource allocation. That is, we use a life history framework to propose an integrative model for understanding how OT functions to affect resource allocations. Our proposals are necessarily preliminary, but, we think, proposals of the kind we offer are needed for further progress toward conceptual integration; our proposals illustrate this broader point.

Fourth, we discuss caveats, unanswered questions, and future directions of theory and research.

A Life History Framework for Understanding the Function of Endocrine Hormones

Life History Theory

Organisms allocate energy harvested from the environment to fitness-enhancing activities. Energy allocated to one kind of activity is not available for allocation to other kinds. Organisms hence inevitably face *allocation problems*. As some systematic ways of allocating energy promote a particular organism's fitness, given its circumstances, better than others, solutions to these allocation problems evolve through natural selection. In other words, selection sifts through the myriad possible allocation "strategies" that organisms within a species utilize; solutions that make it through selection's sieve tend to be ones that, relative to others, maximize fitness. Other limited resources such as micronutrient building blocks, time, and neural or other tissue-specific resources also give rise to allocation problems. Life history theory seeks to identify how selection shapes organisms' solutions to these allocation problems (e.g., Charnov, 1993; Del Giudice, Gangestad, & Kaplan, 2015).

How an organism can best use limited resources depends on life circumstances. Optimal allocation solutions hence embody contingencies. For instance, an organism's relative body size, current state of pathogen load, level of imminent threat from a predator or conspecific, and immediate opportunities to potentially mate may all affect how the organism should best allocate resources. Because energy and other resources are limited, any decision to allocate additional energy *toward* certain activities (e.g., growth, immune function, defense or flight, mating display or intrasexual competition) inevitably requires, simultaneously, decisions to draw energy *away from* alternative current or future activities.

Endocrine Hormones Within a Life History Framework

Endocrine hormones are released by a gland (e.g., the gonads, the pituitary) into the circulatory system. They then travel to and bind to receptors located in multiple bodily tissues. Binding initiates chains of (p. 319) reactions that affect cellular activity, typically in a tissue-specific manner. Changes in cellular activity then produce phenotypic changes. A hormone's phenotypic manifestations may be numerous and diverse across the many tis-

sues it affects, a phenomenon referred to as *hormonal pleiotropy* (e.g., Flatt, Tu, & Tatar, 2005).

In essence, then, hormones are chemicals that relay messages to multiple cellular "recipients." This essential character of hormones gives rise to a straightforward conceptualization of what endocrine systems have been shaped by selection to do: *These systems were shaped to coordinate simultaneous shifts of energetic and other limited resources from one set of activities to another, contingent on life circumstances* (e.g., Ellison, 2017; Finch & Rose, 1995; Ketterson & Nolan, 1999; Lancaster & Sinervo, 2011). That is, *endocrine systems were designed to mediate allocation decisions*.

We can systematically identify the components of an endocrine system shaped by selection to achieve optimal allocations. Subject to selection are (1) the mechanisms that dictate the circumstances under which a hormone will be released (and then "shut off"), (2) the distribution of receptors that receive signals, and (3) how tissues respond to receipt of signals.

Two additional concepts flesh out this life history view. The first is *phenotypic integration* (e.g., Ketterson, Atwell, & McGlothlin, 2009). The multiple phenotypic changes that hormones coordinate have been selected to "work together" to produce benefits. For example, Ketterson and Nolan (1999) found that, during dark-eyed juncos' mating season, male testosterone increases both attractiveness to females and range size, each of which foster mating success. The second is *allocation trade-offs*. To "pay for" up-regulated effort toward some ends, organisms must down-regulate effort toward others. Some phenotypic changes induced by hormones, then, are beneficial not because they directly produce benefits, but rather because they pay the costs for other beneficial changes. For instance, once again in dark-eyed juncos, male testosterone leads to decrements in parental efforts (e.g., feeding of offspring), not because there is inherent value in doing so, but rather because other efforts—for example, toward finding and attracting mates—are prioritized (Ketterson & Nolan, 1999).

Neuromodulation as Part of an Adaptive Complex of Modulatory Responses

Receptors for a host of hormones reside within the brain, such that hormonal "messages" regulate allocation of neural resources (e.g., allocation of attention to competing stimuli, the appraisal of those stimuli, the potency of particular rewards and punishments). OT, like some other hormones, is projected directly into brain regions, where it acts as a neurotransmitter that up-regulates or down-regulates specific neural networks.

Conditional Responsivity and Internal Regulatory Variables

Once again, allocation solutions should be sensitive to circumstances perceived and interpreted by the organism. The concept of "internal regulatory variables" (Del Giudice et al., 2015; Tooby, Cosmides, Sell, Lieberman, & Sznycer, 2008) reflects appraisals regarding the timing and magnitude of allocation modifications (e.g., of environmental predictabili-

ty, exogenous mortality risk, the state of social relationships, and potentially many other conditions). Organismal systems are designed to secrete hormones in response to these appraisals, which then coordinate reallocations.

Functional Reverse Engineering of Hormonal Coordination

Hormonal effects are phenotypically integrated to yield particular benefits. Hence, nonpsychological effects of hormones, as well as psychological effects, critically inform an understanding of a hormone's specific way of achieving functions. That is, both constrain the range of plausible interpretations of how selection shaped the endocrine system to modulate allocations.

Phylogeny and Adaptation

Phylogenetic perspectives complement adaptationist ones. A hormonal system present now also existed, in some form, in deep evolutionary time. But most likely, it did not coordinate the exact same suite of coordinated outcomes, activated by the exact same circumstances. *Co-option* has occurred when a hormonal system gains a new benefit that did not exist in previous species in a lineage. Co-opted outcomes have been shaped by previous benefits and must serve the new benefit sufficiently well. Secondary adaptation occurs when the new function (or benefit) leads to modification of the system in ways that serve the new function better while maintaining previous functionality (see Gould & Vrba, 1982).

OT illustrates these points well. OT-like peptides had functions in ancestors common to vertebrates and some invertebrates (e.g., mollusks, arthropods, annelids; Gruber, 2014), often pertaining to control (p. 320) of specialized smooth muscle contractions. In an early vertebrate, both OT and vasopressin homologs emerged and evolved to acquire distinct, but sometimes overlapping, functions (e.g., Hoyle, 1999). OT per se debuted in placental mammals ~250 million years ago (Donaldson & Young, 2008; but see also Gwee, Amemiya, Brenner, & Venkatesh, 2008), in which it induces uterine contractions (e.g., Bell, 1909; Dale, 1906), reduces the severity of postpartum hemorrhage (e.g., Elbourne, Prendiville, & Chalmers, 1988; Weitzman, Glatz, & Fisher, 1978), and activates the milk letdown reflex during lactation (e.g., McNeilly, Robinson, Houston, & Howie, 1983; Wakerley & Lincoln, 1973). These events set the stage for an important co-option. In particular, the presence of OT in mothers with newborns, owing to its peripheral reproductive functions facilitating parturition and lactation, may have led it to acquire functions coordinating behavioral aspects of maternal care through OT projections in the central nervous system (Carter, 2014; Crespi, 2016; Feldman, Monakhov, Pratt, & Ebstein, 2016).

OT is now well established as a key mediator of the mother–offspring bond forged during parturition (Carter, 2014), lactation (Crowley & Armstrong, 1992), emotionally "warm" touch (Feldman, Gordon, Schneiderman, Weisman, & Zagoory-Sharon, 2010), and responses to infants' cries (Riem et al., 2011; see also Elmadih et al., 2014). Classic work on rodents demonstrates roles for OT in both establishing and maintaining maternal behav-

ior via particular brain regions (e.g., the nucleus accumbens; e.g., Numan, 2017). OT plays a role in infant responses to mothers too, and the success or failure of this bond's formation early in an infant's life may have long-lasting effects on the OT system (e.g., Fries, Ziegler, Kurian, Jacoris, & Pollak, 2005).

OT likely regulates responses to partners in interdependent social relationships aside from the mother–infant one (e.g., Carter, 2014; Crespi, 2016; Numan & Young, 2016). These effects reflect additional co-options. Crucially, OT's effects on social behavior likely stem from the "biological prototype" for mammalian sociality: the mother–infant bond (e.g., Carter, 2014; Numan & Young, 2016).

Most notably, OT has been co-opted for pair-bonding. Seminal studies focused on voles. Prairie voles form enduring sexual pair-bonds. Montane and meadow voles do not. OT receptors are much denser in members of the monogamous species, in which OT production during mating affects preferences for pair-bond partners (Cho, DeVries, Williams, & Carter, 1999; Insel & Shapiro, 1992; Williams et al., 1994; see also Young & Wang, 2004). This work led to more recent work on human pair-bonded couples. OT administration leads to more engaged, constructive communication about relationship conflicts (Ditzen et al., 2009); more intense orgasms; and greater contentment with a partner following intercourse (Behnia et al., 2014). OT levels predict success of emotional support relationship interventions (Holt-Lunstad, Birmingham, & Light, 2008) and overall relationship satisfaction (Holt-Lunstad, Birmingham, & Light, 2015; but see T. W. Smith et al., 2013). New lovers have elevated OT compared to singles, and OT levels at a relationship's outset predict its success half a year later (Schneiderman, Zagoory-Sharon, Leckman, & Feldman, 2012). (For related effects in marmosets, see Seltzer & Ziegler, 2007; T. W. Smith et al., 2010).[1]

OT perhaps has been co-opted to play roles in yet other interdependent social relationships, such as those between kin, friends, and in-group members (e.g., Crespi, 2016). The OT homologs in birds appear to have acquired some such social functions (Goodson, 2013). And OT may play such roles in some mammals as well (Anacker & Beery, 2013). Although such roles in humans are possible, we offer a cautionary note: As emphasized previously, co-option of OT should not affect social relationships in ways that would markedly compromise its role in the mother–infant relationship. We believe it is more likely that co-option occurred for pair-bonding than for other kinds of social relationships. More work is needed along these lines.

Oxytocin's Psychological Effects and Correlates

A vast literature examining the psychological effects of OT has accumulated over the last 15 years. Although the literature on the associations between levels of OT and behavior or context (outside of maternal behavior) is defined by perhaps a couple dozen studies, over 500 published intranasal administration studies (including some clinical trials) have appeared in scientific journals (see Bos, Panksepp, Bluthé, & van Honk, 2012). The for-

mer, observational studies typically speak to the *causes* or (p. 321) *concomitants* of OT production, whereas the latter, experimental studies speak to *effects* of increased OT.

The Maternal Brain in Rats

Before we review the literature on human OT, we briefly describe classic work on the neurobiology of maternal behavior in rats, as it offers a foundation for understanding proximate mechanisms of OT's psychological effects. Whereas nulliparous female rats actively avoid rat pups, new mothers engage in well-established maternal behaviors with them (e.g., nursing, licking, retrieval from the nest), even when their own pups are experimentally removed and replaced with another mother's pups. Various hormones (e.g., estradiol, progesterone, prolactin) present at birth alter maternal brain structures and lead to these effects (see Numan, 2017).

OT too plays a crucial role in the neurobiological alterations behind maternal behavior. OT projections to the medial preoptic area (MPOA) and ventral tegmental area (VTA) modulate neural input to the nucleus accumbens (NAc). When co-occurring with mesolimbic dopaminergic (DA) activity, OT inhibits NAc activity, which has the effect of releasing inhibition of the ventral pallidum (VP). Resultant VP activity promotes maternal behavior (partly via sensory processing of offspring stimuli, such as scent cues; see Numan et al., 2005; Numan & Stolzenberg, 2009; Stolzenberg & Numan, 2011; Numan, 2017; for similar effects in sheep, see Numan & Young, 2016). These neurobiological networks fundamentally regulate motivation. OT affects pair-bonding in prairie voles through near-identical networks (e.g., once again, OT and DA work together to inhibit NAc control of VP; e.g., Aragona, Liu, Curtis, Stephan, & Wang, 2003; Liu & Wang, 2003; see also Numan & Young, 2016).

OT not only establishes maternal behavior but also maintains it. Though maternal behavior persists even if OT is withdrawn, variations in OT levels postestablishment affect its quality (e.g., Numan, 2017; for correlational work on humans, see Elmadih et al., 2014). OT likely also affects, downstream, cortical systems regulating attentional, cognitive, or emotional processes.

She Loves Me, She Loves Me Not: The OT Paradox

One popularized view is that OT is, metaphorically, the neurobiological "cement" that bonds an individual to another, whether it be mother to infant or one pair-bond partner to another. The OT system has been characterized as one that fosters interest in finding social connection between people—a "calm and connect" system (Uvnäs-Moberg, 2003). As search for connection purportedly promotes prosocial motivation (e.g., trust and trustworthiness; Kosfeld, Heinrichs, Zak, Fischbacher, & Fehr, 2005; Zak, Kurzban, & Matzner, 2005), OT has also been proclaimed to be a "moral molecule" (Zak, 2012).

OT may indeed shape a neurobiological system to promote positive valence of an infant or romantic partner (though, as noted earlier, other hormones promote nurturing behavior too; Numan, 2017). The view that OT generically or unconditionally promotes social con-

nection and prosociality, however, is simply no longer viable. A recent meta-analysis of the effects of OT administration on trust in experimental trust games found no robust overall effect (Nave, Camerer, & McCullough, 2015). Hence, while found to increase trust in some experimental games (Kosfeld et al., 2005), OT has been reported to decrease it in others (Bartz et al., 2011). OT administration has sometimes been found to disrupt social connection, for example, by prompting envy and gloating (Shamay-Tsoory et al., 2009), leading men to perceive less warmth in faces (Hoge et al., 2014), promoting self-interested moral judgments in men (Scheele et al., 2014), and derogating out-groups (De Dreu et al., 2011). Relatedly, some correlational studies report OT to be positively associated with relationship distress (Taylor, Saphire-Bernstein, & Seeman, 2010) and anxiety about romantic relationships (Marazziti et al., 2006; Weisman, Zagoory-Sharon, Schneiderman, Gordon, & Feldman, 2013). After women were asked to think about relational distress, their OT levels increased (Tabak, McCullough, Szeto, Mendez, & McCabe, 2011).

The mixed nature of findings regarding OT's effects on social bonding and connection gives rise to *the oxytocin paradox* (Bethlehem et al., 2014). How can a unified, coherent conceptualization of OT explain its contrasting effects?

Toward Resolving the Oxytocin Paradox

A number of views about what OT does, fundamentally, to produce its psychological effects have been put forward.

OT is fundamentally anxiolytic. In one view, OT dampens reactivity of the hypothalamic-pituitary-adrenal (HPA) axis to threats and, hence, suppresses cortisol responses to stress (e.g., Windle, Shanks, Lightman, & Ingram, 1997). Relatedly, OT may reduce amygdala activity and, thus, suppress fear responses (e.g., Kirsch et al., 2005). Fundamentally, (p. 322) in this view, its psychological effects—for example, on interpersonal trust, perceived trustworthiness of others, willingness to cooperate with in-group members, and interest in affiliation with others—all stem from generalized dampening of stress responses (e.g., Churchland & Winkielman, 2012; Neumann & Slattery, 2016). Influenced by OT, people see other people as less threatening (for details, see Churchland & Winkielman, 2012).

Although OT does suppress anxiety and fear in some circumstances, other findings challenge this view. First, once again, OT administration sometimes leads to diminished trust (see Bethlehem et al., 2014). Second, OT administration may not always suppress stress responses; in some research paradigms, it has promoted episodic memory for aversive events (Striepens et al., 2012), anxiety responses to unpredictable events (Grillon et al., 2013), emotional intensity in response to conflict with partners in men (Ditzen et al., 2012), and Pavlovian fear conditioning (Eckstein et al., 2015). To explain mixed findings, Eckstein et al. (2015) propose that OT has *targeted* anxiolytic effects—specifically, to promote extinction of stress responses (see also Neumann & Slattery, 2016). In absence of conditions conducive to extinction (e.g., when social support is absent), OT may have no

effect (e.g., Heinrichs, Baumgartner, Kirschbaum, & Ehlert, 2003) or even potentiate threat responses.

OT promotes social salience. Another view is that OT heightens the salience of social cues and information (e.g., Bartz et al., 2011; Striepens et al., 2012), largely via effects on dopaminergic reactivity, especially in mesolimbic regions (see Shamay-Tsoory & Abu-Akel, 2016). In this view, OT's effect on perceived safety or threat is context dependent. When social threats are minimal, OT administration should bolster a sense of safety. However, in the presence of social threats, OT should augment perception of those threats.

Although the social salience hypothesis expects that OT will only selectively promote prosociality, it does not uniformly render correct predictions (see Bethlehem et al., 2014). Hence, for instance, whereas OT has been found to promote in-group favoritism, regardless of how the in-group and out-group are appraised (De Dreu et al., 2011), the social salience hypothesis would seem to predict that group appraisals matter.

OT enhances self-referential processing. Yet another view argues that OT enhances emotional interoception—awareness of one's own subjective emotional state (Hurlemann & Scheele, 2016). Like the social salience hypothesis, this view proposes that OT's effects build off of pre-existing psychological appraisals. The difference is that, in this view, self-referential processing, not simply situational construal, is key. Hurlemann and Scheele argue that representations of the self often include close social partners (see Aron & Fraley, 1999). Accordingly, people may be especially sensitive to social information emanating from close social partners, who are seen as part of the "self."

OT modifies reward sensitivity. Neurobiological studies of rats, once again, establish that OT receptors populate dopaminergic mesolimbic structures, notably the VTA and NAc, which are known to importantly regulate reward sensitivity: detection of rewarding stimuli, tracking and reinforcement of behaviors leading to reinforcing consequences, and attention to discriminative cues upon which reinforcement is contingent. OT, then, may exert its major psychological effects through modification of these reward circuits (see Bethlehem et al., 2014; Numan & Young, 2016).

A cascade of effects. Naturally, OT need not have psychological effects through just one route. Indeed, at a neurobiological level, OT affects, directly and through downstream influences, multiple structures and systems (Numan, 2017). Perhaps the most sensible view, then, is that OT affects motivation *and* cortisol responsivity *and* attention (both to external stimuli and interoceptively). Of course, this view, while likely, requires that key questions be answered: Through what processes does it do so? How are these effects functionally coordinated? How does the OT system "work"? Answers to these questions, in our minds, require an understanding of the evolved (and likely current) contexts in which OT exerted its important psychological effects.

The Mother–Infant Prototype Revisited

Once again, OT's effects on social behavior in mammals likely debuted evolutionarily in the context of maternal–infant interactions. And, although its psychological effects may have been co-opted and modified for other social contexts, modification of the OT system should not seriously disrupt its functionality within the maternal–infant relationship. That is, OT's psychological effects likely evolved because they promoted maternal care for and protection of an infant, and, in a maternal–infant relationship, they should still do so.

(p. 323) With this assumption in mind, let us reflect on proposed conceptualizations about how OT affects psychological processing. The social salience hypothesis argues that OT renders social cues salient and nonsocial cues less salient. A related view claims that OT potentiates social rewards and de-potentiates nonsocial ones. Would these effects promote maternal care for an infant in the context of a maternal–infant relationship? OT may facilitate proficient maternal care if it were to render salient social cues *emitted by the infant* or promote the social reward value of cues of *infant* responsiveness and well-being. Yet *generalized* salience of social cues or potentiation of social rewards could be expected to degrade the quality of maternal care (e.g., if mothers attended to other social partners rather than their infants). Similarly, one can ask about how OT would promote pair-bonding in these views. Although attention to social cues emitted by a partner or potentiation of rewards in the context of the pair-bond may facilitate bond formation, attention to social cues emitted by others or potentiation of rewards garnered from other social relationships could disrupt pair-bonding.

OT's effects, then, may well be expected to *target* particular relationships. The salience of social cues or modification of social rewards should be "tagged" to specific partners. Indeed, one might expect attention to social cues emitted by some individuals to be diminished. Consistent with this notion, experimental work on rats examining OT's effects on maternal behavior finds that *maternal* motivations are specially affected: It facilitates *maternal care* (e.g., pup carrying, attentiveness to pups, feeding of pups, maternal protective aggression; see, e.g., Numan & Young, 2016).

Targeting of Oxytocin-Facilitated Behavior

How might *targeted* social attention and motivation emerge? In a species in which OT has been co-opted to function in multiple social contexts (e.g., pair-bonding, as well as maternal care), OT's effects should not be tagged to specific phenotypic cues of one class of social targets, such as the faces of infants. Such a system would not permit OT's effects to be tagged to another class of individuals, such as adult pair-bond partners. A more sensible design might tag OT's effects on social relationships that otherwise exert potent motivational effects within the context in which an OT response occurs. For instance, in the context of maternal care, the potent relationship figure is the infant; in the context of pair-bonding, it is the acquired or potential pair-bond partner.

Two important implications follow. First, the *specific* effects of OT will depend on the exact nature of the circumstances in which the OT response occurs (e.g., differ across mother–infant and pair-bond relationships). Second, we cannot fully understand how OT functions without knowing the contexts in which OT increases are naturally experienced. The second implication derives from the first: If OT's specific effects are contingent on the context in which an OT response occurs, then OT's functionality is tied to the contexts in which the OT system is designed to activate.[2]

Natural Circumstances Producing Oxytocin Responses in Romantic Relationships

What, then, are the natural circumstances in which an OT response is produced? For instance, what circumstances in romantic relationships lead to OT responses? Once again, multiple proposals exist. The *calm-and-connect* model (Uvnäs-Moberg, 2003) expects positive associations between OT levels and romantic relationship quality. Some research finds that relationship bonding (expressed by touch or social cues) leads to OT production, which may reinforce nurturing behaviors and thereby facilitate connection between partners (e.g., Grewen, Girdler, Amico, & Light, 2005). By contrast, the *tend-and-befriend* model (see also Mogilski et al., this volume) proposes that distress or anxiety within relationships leads to OT release, which in turn increases "appetite" for social affiliation outside of the distressful bond (Taylor, 2006). Some studies report associations between OT and relationship distress (e.g., Taylor, 2006; Taylor et al., 2010; see also Tabak et al., 2011). (See also T. W. Smith et al., 2013, who found no support for one model over the other.)

(p. 324) In collaboration with others, we propose a third model, the *identify-and-invest* model (Grebe et al., 2017). It follows from the notions we laid out previously. In this view, events that prompt motivation to attend and respond to a relationship partner lead to OT release—most notably, cues that a valued relationship is threatened—which then functions to reorient psychological resources toward the relationship. Romantic relationship threat may arise when individuals themselves are highly invested in those relationships yet their partners are less invested or attentive to them. Grebe et al. (2017) asked romantically involved women and men to think about ways their relationship partners were responsive to them or not and measured the rise or fall of OT as a function of this task. We also administered a battery of measures of relationship involvement to both members of the couple. We regressed individuals' OT response to the task on both self- and partner reports of relationship involvement. Analyses revealed *positive* associations between self-reports of relationship involvement and OT, yet *negative* associations between an individual's OT and his or her *partner's* reports of investment. Consistent with the identify-and-invest model, peripheral OT release was predicted by a *discrepancy* between an individual's own and his or her partner's relationship involvement. Discrepancy prompts motivation to attend to the relationship, which OT purportedly functions to do.

In our view, the identify-and-invest model is compatible with the idea that OT-regulated maternal care constitutes the foundation from which the OT system was co-opted to function to regulate other relationships, such as pair-bonds. OT should function to lead mothers to attend to their infants' needs and protect them in the face of threats. It may make sense, then, that OT's effects co-opted to pair-bonding should lead to attention to the threatened relationship (and not the desire to forge new relationships, as the tend-and-befriend model proposes).

Nonprosocial and Aggressive Responses

The perspective that OT's prosocial effects should be targeted to specific relationships also facilitates an understanding of OT's nonprosocial and aggressive effects. If and when third parties represent threats to infant well-being, adaptive *prosocial* responses with regard to the infant may constitute defensive or *aggressive* responses to third parties. Indeed, in some nonhuman species, OT is widely recognized to promote maternal aggression to protect infants against threats (e.g., predators, threatening conspecifics; e.g., Bosch, Meddle, Beiderbeck, Douglas, & Neumann, 2005).

OT may promote maternal aggression through its anxiolytic effects (specifically, via inhibition of the effect of corticotropin-releasing factor [CRF] in the amygdala on generalized fear responses; Numan, 2017). As defense should be targeted to threats to an infant, however, it seems likely that OT's effects on maternal aggression are also mediated through motivation to protect the infant and, hence, motivated attentional monitoring of threats to the infant. This line of thinking suggests OT may similarly motivate protective responses (and aggressive responses to threatening outside parties) in the context of pair-bonding, fostered by attentional monitoring to relationship threats. The identify-and-invest model fits well with the view that one major function of OT within close relationships is the protection against threats. Circumstances that threaten a relationship are precisely those in which attention to those threats and action to defend against them are called for.[3]

Some scholars propose that OT has been co-opted in humans to regulate social relationships. For instance, OT may facilitate prosocial behavior toward in-group members and defensive behavior toward out-group members (De Dreu et al., 2010, 2011). This view similarly interprets OT's antisocial behavioral effects toward specific parties in terms of its protective or prosocial effects toward other parties.

When individuals were presented with mixed praise and criticism from others, Gao et al. (2016) found that OT administration enhanced salience of praise in women, but fostered salience of criticism in men. They propose that the sex difference may be rooted in different parental roles that women and men played ancestrally and, hence, stem from basic evolved functions of OT. Whereas women's parental duties may have more centrally involved direct caregiving, men may have played a more protective role, guarding against potential harm and threat. (For similar sex differences, see Hoge et al., 2014; Scheele et al., 2014.)

(p. 325) Toward a Life History Model of the Oxytocin System: Integrating Psychological and Physiological Effects

As laid out earlier, within a life history perspective, hormonal systems have fundamentally been shaped by selection to carry out resource allocation decisions; when activated, they lead energy and other resources to be directed toward certain fitness-enhancing activities, while shunting them away from other activities. The many simultaneous effects are phenotypically integrated, working together to promote a benefit or set of benefits in certain conditions—those in which the adjustments paid off ancestrally when the system was shaped. As we furthermore discussed, hormonal systems often adjust both psychological and nonpsychological physiological phenotypes. Even when one is interested in understanding the function of psychological outcomes, nonpsychological effects can inform an understanding of a hormonal system's design. Having discussed OT's psychological effects, we now turn to physiological effects of peripherally circulating OT.

Physiological Effects of Oxytocin

Energy intake and expenditure. OT reduces energy intake and, possibly, increases expenditure. OT administration to rodents, centrally or peripherally, decreases food intake (see Blevins & Baskin, 2015, for an extensive review). The inactivation of OT, either via antagonist administration or receptor blocking, promotes caloric consumption (e.g., Arletti, Benelli, & Bertolini, 1989; Kublaoui, Gemelli, Tolson, Wang, & Zinn, 2008; G. Zhang & Cai, 2011). The neural mediators implicate many of the same brain structures that mediate outcomes on maternal motivation produced by OT: Hypothalamic projections affect the VTA and subsequently, with dopamine, the NAc (e.g., Lawson et al., 2015; Sabatier, Leng, & Menzies, 2013). Increases in central OT selectively affect consumption of carbohydrate-rich foods; they do not affect appetite for fat-rich foods (e.g., Herisson, Brooks, Waas, Levine, & Olszewski, 2014). In male and nonlactating female rats, circulating insulin and glucose activate this system, resulting in diminished rates of feeding (Sladek, Stevens, Song, Johnson, & MacLean, 2016). OT sensitivity to insulin and glucose is blunted in pregnant and lactating female rats, who maintain eating behavior (functionally, to nourish offspring; Sladek et al., 2016; Olszewski et al., 2016).

Researchers have proposed that OT administration may promote weight loss in humans (H. Zhang et al., 2013; see also Blevins et al., 2015). Indeed, a single-dose intranasal OT administration decreased men's caloric intake during a meal by an average of 122 kcal (Lawson et al., 2015). Another study found effects specific to consumption of carbohydrate-rich foods (Ott et al., 2013). At the same time, OT may increase energy expenditure. OT knockout mice develop obesity, even when nutrient intake is constant (Takayanagi et al., 2008; see also Deblon et al., 2011). Cardiac muscle cells in particular utilize more glucose-fueled energy in response to OT exposure (Gutkowska & Jankowski, 2012). OT administration to rhesus monkeys increases resting energy expenditure too (Blevins et al., 2015). Little research has examined metabolic changes as a function of OT administration

in humans. H. Zhang et al. (2013) reported no evidence for changes in resting energy expenditure, though more research is needed.

OT appears to stimulate lipolysis specifically. Rats centrally infused with OT, compared to controls, have greater expression of several enzymes involved in fat metabolism, produce more oleoylethanolamide (a lipid that itself increases fatty acid oxidization), and have lower respiratory exchange ratios, indicating a shift toward fat—rather than carbohydrate—metabolism (Deblon et al., 2011). OT might act directly upon adipocytes, which contain OT receptors (Yi et al., 2015; also reviewed in Blevins & Baskin, 2015; Chaves, Tilelli, Brito, & Brito, 2013).

Taken together, evidence clearly indicates that, outside of pregnancy and lactation, OT negatively affects energy balance. In this sense, then, OT is similar to cortisol, though the sources of mobilized energy differ (lipolysis of triglycerides stored in fat cells vs. gluconeogenesis of energy stored in the liver). In any event, OT releases energy to be used toward some end.

Immunological modulation. In animal models, OT administration reduces inflammation in peripheral tissues (e.g., Nation et al., 2010; Szeto et al., 2013), and it has similar effects on human cells in vitro (Szeto et al., 2008). Yet OT may modulate immune function rather than suppress it (see review in Li et al., 2017; Wang et al., 2015). OT may facilitate wound healing (Detillion, Craft, Glasper, Prendergast, & DeVries, 2004), which in turn results primarily from repair mechanisms operating in the absence of inflammation (Guo & DiPietro, 2010). Immunologists contrast “resistance” functions, such as inflammation, which operate to eradicate pathogens, with “tolerance” functions, such as repair, which **(p. 326)** clean up harm done by pathogens (Schneider & Ayres, 2008). Resistance is immediately more energetically costly than tolerance (and hence the former may be accompanied by “sickness behavior” that energetically “pays for” increased allocation to immune function; Shattuck & Muehlenbein, 2015). OT may shift effort away from resistance and toward tolerance and repair, perhaps to limit immediate allocation of energy toward immune function. Indeed, OT reduces sickness behavior in rats injected with lipopolysaccharide (LPS; Reyes-Lagos et al., 2016). Such modulation could be adaptive if OT release occurred in circumstances that demanded energy allocation to *other* activities. These effects parallel effects of cortisol on costly inflammatory responses; cortisol similarly shifts immune function from resistance functions to tolerance functions (e.g., Garbers et al., 2012), perhaps because it often functions to facilitate adaptive responses to external threats.

Cardiac function. OT receptors richly populate heart tissue. In research on injured and healthy nonhuman animals, OT perfusions into the heart slow heart rate, decrease the force of cardiac myocyte contraction, and suppress blood pressure (Gutkowska & Jankowski, 2012; Hicks et al., 2014). One interpretation is that OT protects and maintains cardiac function through these actions (e.g., by reducing oxidative stress in the heart; Gutkowska & Jankowski, 2012). At the same time, under some conditions, OT administration in lab animals may increase heart rate and blood pressure (reviewed in Blevins & Baskin, 2015). An alternative conceptualization emerges from recent studies. Gamer and

Büchel (2012) administered OT to men who were presented with neutral, positively valenced (happy), or negatively valenced (fearful) faces and asked to perform an emotional classification task. The effect of OT depended on the emotional valence of stimuli; it increased heart rate especially when men were confronted with fearful faces. Gamer and Büchel (2012) propose that OT potentiates the significance of stimuli that evoke approach or avoidance responses. OT administration enhances attention to others' eye region (e.g., Gamer, Zurowski, & Büchel, 2010) and performance in recognizing emotional expression in others, especially avoidance-related (Feeser et al., 2014) or negative emotions (e.g., Striepens et al., 2012; see also Schulze et al., 2011). When OT leads to reductions in heart rate, it may do so through increased parasympathetic control rather than reduced sympathetic control (e.g., Tattersall & Hockey, 1995; see also Norman et al., 2011; Prehn et al., 2013); the former may function to enhance vigilant attention (Kassam, Koslov, & Mendes, 2009).

In fact, the findings that OT perfusions reduce heart rate, strength of contraction, and blood pressure in rodents and dogs are mediated, at least in part, by atrial natriuretic peptide (ANP; e.g., Gutkowska et al., 1997)—which, when released in heart muscle, sensitizes it to parasympathetic control (Atchison & Ackermann, 1990). All in all, OT's effects on heart rate may reflect its role in active, motivated information processing and vigilance for indications of threat, especially in the social environment, an interpretation that contrasts with it reflecting calmness and a sense of safety. This role may be especially important if the natural circumstances that lead to peripheral release of OT call for active, motivated vigilance (e.g., for emotionally significant events). In particular, OT-induced parasympathetic control of heart rate may permit rapid modulation of heart rate in response to stimuli pertinent to threats. As we have already argued, the OT system may respond to potential threats within a relationship context, thereby attuning other systems to detect these potential threats, as well as prepare systems to adaptively respond to threats that are detected by making energy available for utilization, suppressing costly immune function, and rendering the cardiac system ready to respond quickly to emergent events that demand attention and, potentially, action.

Insulin production and sensitivity. In rodents and humans, OT increases the rate of insulin secretion in response to glucose (e.g., Björkstrand, Eriksson, & Uvnäs-Moberg, 1996; Chiodera et al., 1984; Klement et al., 2017) and boosts insulin sensitivity, thereby enhancing glucose uptake by skeletal and heart muscle (e.g., Camerino, 2009; Deblon et al., 2011; Florian, Jankowski, & Gutkowska, 2010; Lee et al., 2008; H. Zhang et al., 2013).

Cortisol has opposite effects in this regard; it induces insulin resistance. Arguably, it does so to maintain levels of circulating glucose needed to fuel the brain during fight or flight; unlike muscles, the brain's uptake of glucose is not insulin dependent (e.g., Ellison, 2017). OT may respond to threats that do not immediately require energetic exertion. Possibly, then, it prepares the body to be able to have energy available for action, should the need arise.

HPA axis responsivity. We noted that OT may suppress HPA responses to threats and other stressors (p. 327) and resulting increases in plasma cortisol levels, mediated by blunted CRF-stimulated release by adrenocorticotropic hormone (ACTH) into circulation (e.g., A. S. Smith et al., 2016). Yet OT's effect on the HPA axis appears to be context specific (Yee et al., 2016). In prairie voles pretreated with OT, corticosterone response to a stressor (walking in shallow water) was not dampened by OT. Rather, OT pretreatment decoupled hypothalamic paraventricular nucleus activity to the stressor from the resulting rise in corticosterone levels and coupled it to autonomic nervous system responses. There, OT permits a glucocorticoid and autonomic response to a stressor when an energetically expensive response (fight or flight) is called for.

OT, then, is not simply a "de-stressor." It may promote vigilance to possible threats and, should an external threat emerge, permit a robust HPA response to it. That might well be an attunement that would promote, for instance, maternal protection against intruders (Bosch et al., 2005).[4]

The OT system conceptualized as an alternative threat-sensitive system. Based on OT's psychological effects, the circumstances in which OT is released peripherally, and OT's physiological effects, we have provisionally proposed a conceptualization of how the OT system has been shaped by selection to carry out resource allocation decisions (Grebe & Gangestad, unpublished). Specifically, we propose that the OT system is responsive to particular kinds of threats or potential threats, and is designed to (1) monitor those threats and (2) respond to them. Hence, we argue, the OT system is itself a threat-sensitive system, much like the cortisol system is a threat-sensitive system. Yet the OT system is distinct from the cortisol system, as the kinds of threats these systems respond to are different.

The OT system responds to potential threats to a valued relationship or relationship partner. We argued this claim, captured by the identify-and-invest model, earlier. The original context in which the OT system evolved to affect behavior is the mother–infant relationship. From the mother's perspective, the infant is a valued relationship partner. The infant is, by its nature, vulnerable to threats—threats that stem from outside agents (e.g., predators, conspecifics), but also threats owing to the fact that the infant's well-being and viability depend on maternal care and responsiveness. In this context, the OT system upregulates (1) vigilance for signs of potential threats to this relationship and relationship partner (e.g., outside agents, infant need states), and attention to those threats, and (2) motivations to respond to these threats. This system was co-opted to operate in the context of pair-bonding. In that context, the OT system operates to protect a valued relationship with a pair-bond partner and, accordingly, is responsive to conditions that threaten the relationship (e.g., when a highly valued partner's relationship involvement is low or uncertain; Grebe et al., 2017).

The psychological consequences of OT under naturally occurring conditions are multiple and depend on the precise context eliciting an OT response. OT likely affects motivational states through neurobiological networks that it fundamentally affects. At the same time, it

likely also influences vigilance and attention downstream, sensitizing individuals to evidence regarding the presence or absence of potential threats. Additionally, it may promote perceived integration of an important other into a sense of self. Yet, we argue, these effects should be defined by the context in which an OT response occurs: Mothers should attend to information pertinent to the safety of their infants, and threatened relationship partners should attend to that relationship. Figure 18.1 depicts the routes through which OT may affect psychological processes, as provisionally proposed within our model.

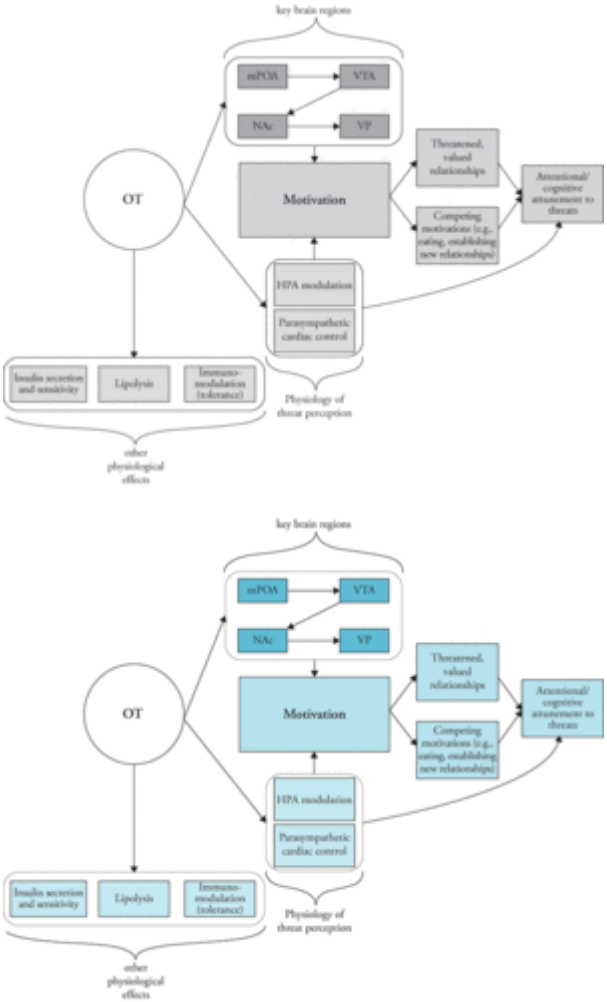

Figure 18.1 A schematic representation of oxytocin's (OT's) functions, with an emphasis on motivational circuits. OT is conceptualized as a system that responds to actual or potential threats to certain classes of relationships via its proximate effects on motivational circuits. These motivational circuits are roughly divided into (1) key regions originally identified as part of the "maternal brain" (see Numan, 2017) and (2) pathways that regulate the physiology of threat perception. Both of these circuits, initiated by OT activity, are proposed to (1) attune motivation toward investment in threatened, valued social bonds and (2) increase vigilance to certain present or future threats. The OT system has other physiological manifestations that may function in part to "free up" resources allocated to the relationship demands responsible for engagement of the OT system. mPOA, medial preoptic area; VTA, ventral tegmental area; NAc, nucleus accumbens; VP, ventral pallidum.

Physiological effects are key components of the OT system for modulating allocation trade-offs. Physiological effects of OT importantly inform our proposal that the OT system is a threat-sensitive system. OT mobilizes energy for utilization. It reduces allocation of energy to energetically expensive immune function. It promotes vigilance to threatening

stimuli while readying the cardiac, insulin, (p. 328) and glucocorticoid systems for rapid responses to demands for action. To be clear, in suggesting that the OT system is an "alternative threat-sensitive" system, we do *not* mean to suggest that, similar to an HPA reaction to a threat, an OT response often leads to a state of active readiness to act, alertness, and subjective feelings of tenseness and anxiety. To the contrary, consistent with others' suggestions, OT may often dampen subjective feelings of anxiety or tenseness. Our proposal that the OT system is a threat-sensitive system is a *functional design* argument: We argue that the system is designed to support adaptive responses to potential threats of particular kinds (e.g., potential threats to the viability of a vulnerable infant) at the cost of reduced capacity to deal with other problems (e.g., reduced inflammatory responses).

Other Outstanding Issues

Additional Roles

The OT system may well have specialized design features to deal with particular kinds of problems, while still playing other roles. The HPA system is a threat-sensitive system, but more functions as a metabolic hormone (e.g., Ellison, 2017). Similarly, the OT system may regulate basic metabolic function (de Jong et al., 2015; Hew-Butler, Noakes, Soldin, & Verbalis, 2008; Onaka, Takayanagi, & Yoshida, 2012; see also Grebe & Gangestad, unpublished).

The Range of Relationships to Which the Oxytocin System Has Been Co-opted to Respond

In mammals and perhaps birds, OT has been adapted to function within the context of parent–offspring (p. 329) and pair-bond relationships. But some scholars have argued that it has been co-opted and secondarily modified to function adaptively in many other relationship contexts as well: with friends, kin, in-group members, out-group members, and strangers. Some evidence is consistent with these proposals. Hence, for instance, Feldman et al. (2010) found that young children's reciprocity with friends positively covaried with their OT levels, themselves predicted by maternal hormone levels and behavior. At the same time, in our view there currently exists little evidence for (or, for that matter, against) OT playing a critical role in these relationships. Much more research is needed to establish its precise role and range of involvement.

Interactions With Other Hormones

OT has well-known interactions with other hormones. In rats, both estradiol and progesterone cause a proliferation of OT receptors in certain brain regions (e.g., hypothalamus) and thereby enhance the effect of infused OT on sexual receptivity (McCarthy, 1995; Schumacher, Coirini, Frankfurt, & McEwen, 1989; Schumacher, Coirini, Pfaff, & McEwen, 1990). Griffin and Flanagan-Cato (2011) note that estradiol and progesterone have differ-

ent structural effects on the ventromedial nucleus in rats, such that the latter should especially enhance OT-primed sexual receptivity. Testosterone has been claimed to have effects that oppose those of OT (e.g., Crespi, 2016), but some evidence showing positive covariation between these hormones in men might lead one to wonder about this conceptualization (Jaeggi, Trumble, Kaplan, & Gurven, 2015). Interactions between testosterone and OT are also of interest. Finally, OT may interact with opioids to affect social outcomes (see review in Gangestad & Grebe, 2017).

Variability in Responsivity of the Oxytocin System

Not all mothers demonstrate the same responsivity of the OT system. For instance, maternal depression predicts lower responsivity of the OT system both prenatally and during lactation (for a review, see Moura, Canavarro, & Figueiredo-Bragas, 2016). Mothers who have fewer resources, both physical and social in nature, may evidence lower OT responsivity to their infants. Although the literature to date proposes that the OT system of depressed mothers exhibits “dysfunction” (Moura et al., 2016, p. 561), from a life history perspective this variation may reflect adaptation, with maternal OT regulating a trade-off between dedicated attention to an infant and attention to competing demands. Ancestrally, mothers with greater resources and social support may have benefited from (or, in effect, been able to afford) greater attention to infants. The OT system may have accordingly evolved to be sensitive to information pertaining to resources and social support.

Conclusion

OT is now a hot topic within social endocrinology and psychology, more generally. Hundreds of published empirical studies have examined its effects. At the same time, consensus on an overarching perspective—how empirical findings should be organized under an umbrella of how the OT system fundamentally *works*—remains elusive. In this chapter, we have reviewed the primary proposals that have been put forward. We have also argued that a perspective rooted in evolutionary biology, in which OT is understood as a mediator of life history trade-offs, offers one potentially fruitful way forward. We offer one possible interpretation along these lines and discuss evidence consistent with it. Nonetheless, key questions remain unanswered. Perhaps most foundationally, a life history perspective’s fundamental strength is that it seeks to understand any particular hormonal system in ways guided by what is known about the evolutionary forces that give rise to and shape the design of hormonal systems. Ultimately, an adequate social endocrinological understanding of OT will be an *evolutionary* social endocrinological understanding.

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Notes:

([1]) The OT homolog present in passerine birds (mesotocin) may or may not play similar roles in pair-bonding. Although some research suggests it does (Klatt & Goodson, 2013; Lowrey & Tomaszycki, 2014; Pedersen & Tomaszycki, 2012; for effects of vasotocin, see also Baran, Tomaszycki, & Adkins-Regan, 2016), whether mesotocin's role in either maternal care or pair-bonding is widespread across bird species remains unknown.

([2]) Methodologically, this means that the functionality of the OT system cannot be understood through experimental administration studies alone. In administration experiments, OT's effects are examined within contexts chosen by the experimenters, not contexts in which OT secretions and projections naturally occur. Furthermore, OT administration outside the presence of a natural circumstance that would produce OT secretion may evoke a response, but one that bears little similarity to the response produced in any natural circumstance leading to OT secretion.

Other methodological limitations of OT administration studies have recently received attention. The typical administration study is woefully underpowered to detect small to moderate effects (power ~15 percent; Walum, Waldman, & Young, 2016). Moreover, intranasal administration results in massive increases in peripheral levels, but only a small amount is absorbed centrally, such that some effects may be downstream behavioral outcomes arising from peripheral effects (e.g., on heart rate; Leng & Ludwig, 2016).

([3]) Earlier, we emphasized a limitation of OT administration studies: OT may be administered in contexts in which OT is never naturally projected centrally (at levels attained). Though OT may have effects in such contexts, their effects may not be understandable in terms of adaptive response to particular circumstances. The point may be illustrated by antisocial effects: These effects may actually be *prosocial or protective with regard to other relationships*, but if OT administration occurs in the absence of such a relationship, the study does not readily lend itself to such an interpretation.

([4]) In addition to these major physiological effects, OT has several others, which we mention briefly. Most notably, it has effects consistent with its fundamental role as a smooth muscle contractor (Altura & Altura, 1977)—during labor, lactation, and orgasm/ejaculation, OT binds to receptors on the respective muscle fibers, inducing calcium ion mobi-

lization and subsequent contraction (Tahara et al., 2000; see also Conklin, Smith, & Olson, 1999). These effects, however, need not be coordinated with the physiological effects we describe. OT's well-established role in parturition (indeed, its name derives from Greek roots for "quick birth") results partly from a rapid and transitory proliferation of OT receptors in uterine tissue, where OT is locally synthesized (at least in primates; Gimpl & Fahrenholz, 2001). OT is produced in male testes too, where it is involved in sperm transport and androgen synthesis (Gimpl & Fahrenholz, 2001). Naturally, OT produces milk letdown through smooth muscle control. As already noted, some effects of OT (e.g., decrease in eating) are blocked during lactation and, hence, are decoupled from other coordinated outcomes.

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