Motivation Science

© 2022 American Psychological Association
ISSN: 2333-8113

2022, Vol. 8, No. 2, 81–105
https://doi.org/10.1037/mot0000260

Neuroendocrine Mechanisms of Aggression in Rodents

Nathaniel S. Rieger[1], Caleigh D. Guoynes[2], Patrick K. Monari[2], Emma R. Hammond[2],
Candice L. Malone[2], and Catherine A. Marler[2]
[1] Department of Psychology and Neuroscience, Boston College
[2] Department of Psychology, University of Wisconsin-Madison

Exploration into the biological bases of aggression has demonstrated the existence of many forms of aggression. Here we investigate the neuroendocrine bases of these types of aggression in rodents. With this, a new emphasis on appetitive and consummatory aggression, and how this framework illuminates our understanding of human aggression, is reviewed. This article reviews several specific types of aggression, starting with the development of aggression, maternal aggression, male-male and female-female aggression, and ending with seasonal aggression. We take an initial ethological perspective and then provide evidence for links between neuroendocrine compounds and aggression. Applications to the understanding of human aggression are provided when appropriate. The review reveals the many neuroendocrine drivers of aggression, including sex steroid hormones, hormones involved in the stress axis, the neuropeptides oxytocin and vasopressin, the neurotransmitters GABA, glutamate, serotonin, and dopamine, and the hormone melatonin. We further incorporate brain circuits integrating aggression and neuroendocrinology that includes the social neural network. Overall, the neuroendocrine control of aggression is sophisticated and allows for a significant level of control of aggression through both stimulatory and inhibitory mechanisms.

Keywords: steroid hormones, consummatory aggression, appetitive aggression, serotonin, development

The decision to approach and interact with another individual, termed social approach, represents one of the most basic components of social engagement. However, such approach behaviors are overlaid by critical interactions with the environment that relate to both the social salience of conspecific behavior and the physical surroundings. Based on these factors, individuals may choose to instigate one of a number of social interactions, including aggression. Aggression is an important subset of social approach and is expressed in differential ways depending on the situation (Fuxjager et al., 2018). Thus, integration of different contexts and past experience is essential for understanding the expression of aggression. Here we focus on an ethological and neuroendocrine perspective examining what influences both the motivation to approach a member of the same species and the decision to escalate interactions to displays of strength or even violence.

Social behavior has its costs and benefits and there are multiple permutations of these across species. Among the advantages of expressing both aggressive approach and the act of fighting is defending a family unit or resources against a social challenge, allowing survival and reproduction. A lack of aggression toward intruders can, in contrast, translate into decreased food resources, decreased ability to mate guard, decreased access to mates, increased infanticide from conspecifics toward offspring, decreased access to shelter, and so on. There is a balance to be maintained, influenced by different environmental contexts that may help to explain why there are a multitude of mechanisms underlying the expression of aggression. There are, nonetheless, overarching themes that may help to understand how individuals express an appropriate level of aggression. Seeking out or escalating aggression during inappropriate contexts can be detrimental, termed maladaptive aggression, and too little aggression can result in lack of access to resources through losses in competition that can further morph into chronic social defeat (Greenberg et al., 2015) requiring a balance between knowing when to aggress and when to avoid or stop confrontations. An excellent example of the balance is provided by a study with house mice examining how aggression can be modified through competing stimuli (Burnett et al., 2019): aggression toward an intruder is decreased when hunger levels are increased via food manipulations and stimulation of agouti-related peptide (AGrP) neurons (increases feeding behavior) in the arcuate nucleus located in the hypothalamus. Both large and subtle adjustments of aggressive motivation are needed to respond to a changing environment.

Aggression, in its adaptive form, functions to compete with other individuals and gain access to resources through either direct

---

Nathaniel S. Rieger https://orcid.org/0000-0002-5147-4164
Caleigh D. Guoynes https://orcid.org/0000-0003-4512-9652
Patrick K. Monari https://orcid.org/0000-0003-4699-3004
Candice L. Malone https://orcid.org/0000-0003-3008-5570
Catherine A. Marler https://orcid.org/0000-0002-2783-1029

This was supported by NSF grant IOS-1946613.

Correspondence concerning this article should be addressed to Catherine A. Marler, Department of Psychology, University of Wisconsin-Madison, 1202 W. Johnson St., Madison, WI 53706, United States. Email: catherine.marler@wisc.edu

physical aggression and/or display (advertisement) behavior. In animals it can involve behavior with the goal of injuring another individual (Attili & Hinde, 1986), but aggressive motivation can also be conveyed through display behavior to settle competitions without the aggressor or aggressee becoming injured, as would also be true after a dominance hierarchy has been formed. Understanding the neuroendocrine control of aggressive motivation helps in understanding some of the mechanisms that might result in maladaptive aggression where an individual may (a) seek out aggressive interactions and (b) ignore social signals that escalate aggression in inappropriate contexts. Below, we add discussions of maladaptive aggression that may be particularly relevant to the human condition. To explore aggressive motivation from the external ecological environment to the internal underpinnings, we also include an overview of essential brain areas and neural circuits when possible. Our primary focus in this review is on rodents to both limit the scope of the review and to include neural and genetic manipulations where available. Here we review some of the different types of aggression that are defined based on the context in which it occurs, ranging from the development of aggression during early life to adult aggression. We explore the development of aggression including play fighting, territorial aggression, maternal aggression and long-term seasonal changes in aggression, but begin by investigating two behavioral components that have recently been used to address separate components of aggression, those of appetitive and consummatory aggression that are associated with specific neural circuits.

Appetitive and Consummatory Aggression

Recently, aggression has been defined as having two overarching phases, the appetitive (aggression seeking) and consummatory (attack) phases. Generally speaking, appetitive aggression is the act of seeking out, but not carrying out, aggression and is driven by the rewarding aspects of consummatory aggression causing animals to seek opportunities for aggression even when unwarranted or potentially harmful (Golden et al., 2019). Studying appetitive aggression is of particular interest to researchers who seek to understand the neural circuitry that may underlie recidivism rates in previous violent offenders that leads to relapse to aggressive behavior. Consummatory aggression conversely is the actual act of carrying out aggression or attacking another (Golden et al., 2019). As discussed below, both consummatory and appetitive aggression can be either adaptive or maladaptive dependent on the context. The act of carrying out this aggression, particularly winning fights, is generally considered rewarding leading to future appetitive aggression and showing how the two phases of aggression can overlap. As such, it is of great interest to understand both how the decision to aggress and the process of aggression should occur in an adaptive sense and how these systems are perturbed leading to inappropriate or pathological aggression. Thus, researchers have worked to understand the circuits that underlie both appetitive and consummatory aggression (see Figure 1).

With knowledge of the mammalian aggression circuit born out of studies of adaptive aggression (generally using resident intruder paradigms that mimic territoriality) we can then try to better understand what drives maladaptive aggression. Understanding why pathological aggression occurs is a question of great clinical relevance as many neuropsychiatric disorders manifest with maladaptive aggression. Thus, revealing the underlying neurocircuitry perturbations can inform future therapeutic treatments. Importantly, appetitive and consummatory aggression are at least partially dissociable (Golden, Jin, & Shaham, 2019). While in many cases, neuromodulators that affect one of these processes also affects the other, such as GABAa receptor (Miczek et al., 2002), modulation increasing both aggression and aggression seeking, in other cases, consummatory and appetitive aggression may be regulated differently, as is the case with modulation of glutamate receptors (Takahashi & Miczek, 2014). With this, while some of the same brain regions driving appetitive and consummatory aggression are the same (such as the VMH and NAc), appetitive aggression also includes different brain regions, notably the ventral tegmental area (VTA) and lateral habenula (LHb; Aleyasin et al., 2018; Flanigan et al., 2017; Golden et al., 2016).

Consummatory Aggression

Consummatory aggression (Hashikawa et al., 2016), or the act of actually carrying out aggressive behaviors, is considered to be adaptive (Scott, 1966) when individuals recognize an aggression-inducing stimulus and subsequently engage in aggressive displays or fighting *only* to the level necessary to achieve their desired outcome (Lischinsky & Lin, 2020), Consummatory aggression is a potentially costly behavior due to the danger of physical harm but is prevalent across species and generally follows the same pattern, using physical displays and fighting to overpower an opponent (Lischinsky & Lin, 2020). While these processes have been studied using a variety of paradigms in order to understand each specific type, they share a general overall process by which they occur. That is animals must (a) take in a relevant external cue and recognize the need for aggression and (b) initiate an attack or defense via motor output (Lischinsky & Lin, 2020). Understanding the circuits that underlie both appetitive and consummatory aggression then can inform our knowledge of both adaptive and maladaptive aggression.

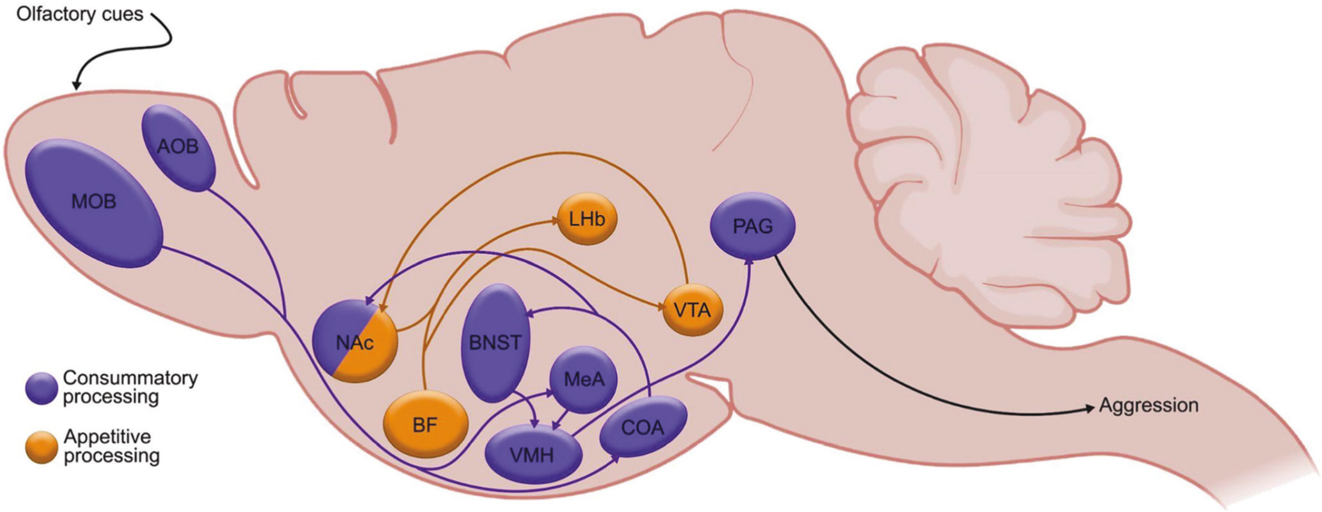
Consummatory Aggression Circuits

Sensory inputs to the brain from external cues drive an animal's recognition for the need for aggression (Lischinsky & Lin, 2020), although this can vary based on the sensory circuit primarily used for social interactions in a particular species. In the case of rodents, this recognition is largely driven by olfactory cues following social exploration (Albers, 2012; Edwards et al., 1993). The initial brain regions responsible for processing olfactory cues are the main olfactory bulb (MOB) and the accessory olfactory bulb (AOB) and, importantly, rodents without olfactory bulbs show profoundly decreased aggression (Hashikawa et al., 2016). The AOB pathway drives investigation and projects directly to the medial amygdala (MeA; Hashikawa et al., 2016, 2018; Unger et al., 2014), also a target of the MOB. The MOB pathway is essential for approach behavior as it first projects onto the cortical amygdala (COA) and silencing this region prevents both approach and avoidance (Hashikawa et al., 2016). The COA then passes information to a number of brain regions including the NAc—important to aggression and reward discussed below, the bed nucleus of the stria terminalis (BNST) – important to the onset of aggression, the substantia innominate (SI) and the MeA (Lischinsky & Lin, 2020).

Aggression is then driven by the circuits downstream of the MeA because it is the first place where both AOB and MOB

Figure 1

Schematic Illustration of a Sagittal Section of Neuroanatomical Pathways for Consummatory (Purple) and Appetitive (Orange) Aggression in Rodents



Note. An understanding of the pathways for appetitive aggression is less well developed compared to consummatory aggression. AOB = accessory olfactory bulb; BF = basal forebrain; BNST = bed nucleus of the stria terminalis; COA = cortical amygdala; LHb = lateral habenula; MeA = medial amygdala; MOB = main olfactory bulb; NAc = nucleus accumbens; PAG = periaqueductal gray; VMH = ventromedial hypothalamus; VTA = ventral tegmental area. See the online article for the color version of this figure.

information becomes integrated and it is active in aggression. This is driven by GABAergic cells as the activation of GABA increases attacks, while its suppression decreases attacks (Hu et al., 2021; Morrison et al., 2014; (Takahashi & Miczek, 2014). With this, factors that affect the excitatory-inhibitory balance of different brain regions through activation of GABA and glutamate activity may play an important role in both adaptive and maladaptive aggression (Lewis et al., 2018). Perhaps most importantly though, the MeA has strong connections to the ventrolateral portion of the ventromedial hypothalamus (VMH), an extensively studied brain region that is vital to aggression in rodents (Simerly et al., 1990). The VMH also receives inputs from the BNST and activating this region increases attacking behavior in male-male encounters while ablating this region blocks both male-male aggression and maternal aggression (Hasen & Gammie, 2006). The VMH is responsible for both offensive aggression, or attacking an opponent, through estrogen receptor positive cells and for self-defense based aggression, defending oneself from another (Delville et al., 1998; Lonstein & Gammie, 2002). These taken together show that the VMH is important to aggression across contexts. The VMH then sends information to the periaqueductal gray (PAG) which acts as the motor output necessary to drive the initiation of physical attacks (Hashikawa et al., 2016). The circuit described above, then, has broad application across aggressive contexts and thus many studies of pathological aggression focus on these regions and what drives either the rewarding aspect of seeking out aggression or the inappropriate expression of aggression as will be described below.

Appetitive Aggression

Appetitive aggression encompasses the motivation to aggress against another, and in particular the process by which an individual seeks out aggression (Golden, Jin, & Shaham, 2019, Golden, Jin, Heins, et al., 2019; Jennings et al., 2015). Appetitive aggression is of particular interest in the study of maladaptive aggression, or when animals, in particular humans, agress when they should not, or escalate beyond what is contextually within reason (Golden et al., 2016; Neumann et al., 2010; Tielbeek et al., 2018). This has often been studied in the context of reward, and in fact aggression seeking closely resembles the actions of drug seeking (Golden & Shaham, 2018). Maladaptive aggression is of particular interest in humans because it is a hallmark of different pathologies and leads to a number of severely negative clinical outcomes, and can be modeled in rodent species.

In particular, researchers are seeking to understand what circuits drive the motivation to seek out aggression and how these circuits are affected by substance use disorders and neuropathologies that seem to make aggression particularly rewarding. As such, researchers often use behavioral paradigms tied to reward seeking to test these procedures. For example, many studies of appetitive aggression use either conditioned place preference, showing that animals prefer to spend time in a location where they have previously had aggressive encounters (similar to how they prefer to spend time where they have previously been administered rewarding drugs) or operant paradigms, where animals nose poke or lever press in order to gain access to an opportunity for aggressive encounter (Golden, Jin, & Shaham, 2019). These studies have shown that aggression is rewarding and that aggression seeking is increased by previous aggressive encounters, and relapse to aggression seeking, similar to substance use relapse, can occur in animals that have previously had aggression as a reward.

While many studies of appetitive aggression are interested in maladaptive or pathological aggression, appetitive aggression has its roots in an ecological phenomenon. The winner effect occurs across species and is a process by which an individual wins fights leading to them winning subsequent fights and often initiating fights faster (Hsu et al., 2006; Oyegbile & Marler, 2005). This can be studied in the lab using an operant mechanism by which an animal nose pokes in order to gain access to, and initiate aggression toward, a smaller weaker conspecific (Golden, Jin, & Shaham, 2019). The majority of these studies occur in house mice and provided one of the first paradigms to show that a species outside of humans would learn to seek out the opportunity to fight, thus implying that this process is rewarding beyond humans and providing a model of clinical aggression.

Appetitive Aggression Circuits

The main circuits that underly appetitive aggression include the basal forebrain, the VTA, the NAc and the LHb (Flanigan et al., 2017). This specific circuit is distinct to appetitive aggression. This circuit is mainly driven by dopaminergic projections from VTA to NAc (two brain nuclei associated with reward; Golden, Jin, & Shaham, 2019). Importantly, aggressive attacks against a generally weaker opponent increase dopamine (DA), a neurotransmitter also associated with reward and reinforcement in the VTA and lead to activation of the NAc and increased extracellular DA in the NAc (Golden, Jin, Heins, et al., 2019). The NAc has GABAergic projection neurons that express two types of DA receptors that project to the LHb: DA receptor 1 and DA receptor 2. If blocked with a DA receptor 1 or 2 antagonist, aggression seeking (in the form of self-administration of aggression) is decreased while not necessarily altering consummatory aggression (Golden, Jin, & Shaham, 2019). The LHb receives inputs from both the NAc and basal forebrain and increases aggressive conditioned place preference when the basal forebrain to LHb pathway is activated (Flanigan et al., 2017; Golden et al., 2016).

Appetitive and Consummatory Aggression Summary

Taken together, we then see that aggression is made up of two parts, a motivation to aggress (appetitive) and carrying out of aggression (consummatory). The actions of specific neurotransmitters and drugs in these systems have shown that these two systems are at least partially distinct. For example, $GABA_A$ manipulations have a dose dependent effect on aggression seeking versus aggression severity in mice. At low doses, allopregnanolone, a GABA agonist, increases aggression seeking but does not alter attack severity, but this effect is reversed at high doses (Fish et al., 2002). Glutamate also plays a role in this with glutamate antagonists causing a decrease in number of attacks but not affecting operant aggression seeking (Takahashi et al., 2011). Both the appetitive and consummatory phases are important but the consummatory phase is the particular driver for adaptive forms of aggression while it appears that the appetitive phase is particularly important to maladaptive aggression. These processes have overlapping but distinct neural circuitry and understanding how they interact especially at the nodes where they overlap will likely give us a greater knowledge of how aggression works and why it goes wrong in clinical settings.

One interesting aspect of these circuits is the existence of sex differences. Importantly, males tend to show more ability to learn to nose poke for aggression (a learned operant behavior), indicating that aggression may be more rewarding to males than females, presenting a case for greater motivation for appetitive aggression (Hashikawa et al., 2016). Interestingly both the MeA and BNST of rodents are sexually dimorphic and this could lead to differences in aggression across the sexes, but further studies will need to be done. Because of the higher level of aggression in males of many rodent species, the vast majority of studies on aggression have been done on males. These sex differences, however, may mean that the findings from these studies are not applicable to both sexes, and limits their generalizability to primate species. Some primates, such as the common marmoset (*Callithrix jacchus*) have been reported to have increased aggression in females, and other primates such as the rhesus macaque and Japanese macaque have been shown to have a complex interaction between sex, aggression, social context and social rank (Eaton et al., 1986; Kulik et al., 2015; Michels, 1998).

Development of Aggression

In many group-living animals, expressing appropriate adult aggression requires a fine balance between optimizing mating opportunities and reducing chance of injury. For these species, practicing aggression in the form of social play may be particularly important because it can help animals make contextual adjustments of their actions based on feedback from play partners (Pellis & Pellis, 2017). Social play is characterized by appetitive aggression while generally lacking the highest escalation of the consummatory component of aggression that can lead to injury. In addition, it is often greater in males compared to females. Interestingly, communal rearing, that would increase juvenile contact, can improve competitive abilities (Fischer et al., 2018).

An adaptive mechanism for increasing expression of a behavior is through the reward systems. For example, social play can be increased in juveniles through activation of the opioid reward system (Vanderschuren et al., 2016; Zhao et al., 2020). Play behavior can also be modified by experience. For example, play is enhanced when animals have experienced social isolation (Guerra et al., 1999; Holloway & Suter, 2004; Ikemoto & Panksepp, 1992). We can also ask whether the lack of play has consequences for future aggression? Deprivation of social play can lead to both maladaptive adult aggression in resident-intruder interactions (van den Berg et al., 1999) and defeat-induced social avoidance in both adult females and males (Kyle et al., 2019). Thus, juveniles have both a high drive for social play and neurobiological mechanisms that reinforce the behavior. However, there are several species that display high levels of adult aggression, but do not show robust juvenile social play—some of these species include California mice and prairie voles (personal observations and Pellis et al.1989), two monogamous species.

Aggression can first manifest as social play which can then transition into full aggression during puberty. Understanding how this occurs is vital to understanding adult aggressive behaviors. At birth, most mammals lack the coordination, strength, and social experience to be successful in aggressive encounters. Therefore, early stages of development are devoted to increasing physical coordination and strength (Le Roy et al., 2001; Walton et al., 1992). Beyond increasing strength and coordination, there can also be specific behavioral changes related to the goals of aggression as it switches from play fighting to serious goal-directed fighting. The highly aggressive and territorial golden (Syrian) hamster, for example, displays distinct changes in behavior during the transition from play to adult fighting. Adolescent hamsters shift from attacking the face/front of an intruder, representative of defensive aggression, to the rear and belly of an intruder as they age (which is more representative of offensive aggression; Wommack et al., 2005; Wommack & Delville, 2007b). However, these distinct phases are not present in all rodents transitioning from play to adult aggression. In preparation for independence and adulthood, the peri-adolescent phase of development is marked by changes to hormone and neuropeptide systems that support physical, social, and cognitive development (Cameron, 2004; Gee et al., 2018; Griffin, 2017; Spear, 2000). The development of aggression may therefore rely on species-specific competition demands and be driven by differences in hormone and neuromodulator levels. Hormone changes and social experience during this peri-adolescent phase are critical for expression of appropriate aggression phenotypes in adulthood (Bell, 2018; Ramirez, 2003; Sachser et al., 2018; Susman et al., 1987). In this review, we will focus on specific developmental changes to steroids (testosterone, estrogen, corticosterone, glucocorticoids), neurotransmitters (GABA, glutamate, serotonin, DA), and neuropeptides (OXY, arginine vasopressin [AVP]) that influence adult aggression.

Testosterone and Estrogen

One of the hallmark signs of adolescence is the maturity of the primary sex organs and the subsequent increase in sex steroids that help shape brain maturation (Grotzinger et al., 2018; Herting et al., 2014; Schulz et al., 2009). A primary emphasis has been on the androgen testosterone; males typically play more during development than females. In male rats, a neonatal testosterone surge increased play-fighting in juveniles but did not influence adult aggression later in life (Pellis et al., 1989), and pubertal testosterone injections increased short-term aggression in male rats (Farrell & McGinnis, 2003). These studies indicate that higher neonatal testosterone may influence the rewarding nongoal oriented behavior of play but not the goal-directed aggression of adults. In male California mice, prepubertal castration made adult males more likely to show social defeat after an aggressive encounter, but adult replacement of testosterone or dihydrotestosterone (DHT) reversed these effects (Wright et al., 2020). This suggests that testosterone during adolescence is also important for adult resilience to aggression. Testosterone and adult aggression are also influenced by early-life stress; adult male mice that experienced early-life maternal separation showed decreased aggression as adults and had lower plasma testosterone levels compared to controls (Tsuda et al., 2011). This suggests that early-life stress may alter the developmental trajectory of androgen effects and decrease adult testosterone levels and adult aggression. However, in highly aggressive golden hamsters, adults show less aggression than prepubertal hamsters and the presence or absence of testosterone does not seem to underlie this relationship (Romeo et al., 2003). Overall, these data suggest a positive association between adolescent testosterone and aggression but underscore that level of testosterone does not influence all species.

Early life experience related to parental care can also influence testosterone and the neurodevelopment of aggression. Prior to adolescence, it is interesting that in California mice there are Testosterone pulses in response to pup retrieval behavior (moving the pup to a different, possibly safer location; Becker et al., 2010; Fuxjager & Marler, 2010) by the father during the juvenile period (between birth and adolescence) that is largely viewed as quiescent with respect to testosterone levels. These retrievals likely remove the pups from dangers that might result in pup harm or well-being (Marler et al., 2003). The experience of increased retrievals by fathers increases resident-intruder aggression and an increase in AVP staining in the dorsal BNST (AVP is androgen dependent) of the male offspring (Frazier et al., 2006). Moreover, the most recent paper linking aggression, AVP and testosterone provides a growing body of evidence for mechanisms behind cross generational behavioral transmission of aggression (reviewed in Becker et al., 2021). This provides a link between early experience and adult aggression.

Fewer studies have examined the developmental role of estrogen on adult aggression, but available studies suggest both a role for estrogen receptors and sex differences. The developmental and adult inactivation of estrogen receptor-alpha (ERα) increases aggression in females but decreases aggression in males (Ogawa et al., 1998, 1998). The opposite effect is found for estrogen receptor-Beta (ERβ) knockout mice; female knockout mice show reduced aggression and male knockout mice show increased aggression toward intruders (Nomura et al., 2002; Ogawa et al., 1999). In addition, male mice with a mutation that made them insensitive to androgen binding but sensitive to aromatized estrogen binding were more likely to retain some juvenile forms of playful defense compared to control males (Field et al., 2006). This suggests that in addition to androgen receptor activation, estrogen receptors may also play an important role in the transition to adult aggression. With the greater level of aggression and aggressive play behavior exhibited by male rodents, it is not surprising that Testosterone influences play behavior that contains many of the components of adult aggression.

Glucocorticoids/Cortisol

The appropriate development of the hypothalamic–pituitary–adrenal (HPA), or stress, axis during puberty also impacts aggression. Losing adult aggressive contests is stressful and can lead to activation of the HPA axis via cortisol. However, while adults that lose a single aggressive encounter will have many behavioral and neuroendocrine consequences, juveniles only show transient behavioral effects in response to repeated losses (Wommack & Delville, 2007a). This suggests that the development and maturity of the HPA axis may mediate plasticity in aggression. The lateral septum (LS) seems to be an important area controlling this behavior as play-fighting increased CRH fiber density by 100% and showed a 75% increase in double-labeling with c-*fos* after a play-fighting bout (Cheng & Delville, 2010). This indicates that the LS is likely involved in both the consummatory and appetitive phases of play-fighting. Similar effects of stress have been observed in rats. Maternal separation increased offensive play-fighting in juvenile male rats and was correlated with higher plasma corticosterone levels (Veenema & Neumann, 2009). However, in monogamous mandarin voles, paternal deprivation during peak play-fighting (postnatal day 35), increased plasma corticosterone levels but decreased offensive play-fighting behaviors (Wang et al., 2012). This demonstrates the overt impact of early cortisol/stressor exposure on the agonistic developmental trajectory and aggression tendencies to different social stimuli. Adolescents that were exposed to social stress, presumably activating the HPA axis, frequently attacked smaller intruders more readily but did not attack weight-balanced intruders as quickly as controls (Delville et al., 1998), suggestive of bullying behavior. In pubertal golden hamsters, increased pubertal stress increased cortisol levels and induced a more rapid transition from play-fighting to adult agonistic behavior in adolescent hamsters (Wommack et al., 2005). This effect can be blocked by coadministering corticosteroid type II receptor antagonists with the stressor (Wommack & Delville, 2007b). Increases in cortisol resulting from social stressors also altered resident—intruder aggression in adolescent golden hamsters (Delville et al., 1998). In summary, activation of the HPA axis can stimulate play fighting, although not in all species, but also potentially influence the transition from play fighting to more adult-like aggression.

GABA and Glutamate

Both GABA and glutamate play critical roles in the development of the HPA axis and stress response. GABAergic neurons can inhibit excitatory signals in the BNST, POA, and hypothalamus, areas known for their role in aggression (Herman et al., 2004). In male golden hamsters, activation of latero-anterior hypothalamus (LAH) $GABA_A$ receptors increased adolescent androgenic-anabolic steroid (AAS)-induced aggression by suppressing juvenile play behaviors in favor of more mature forms of aggression such as belly and rear attacks (Morrison et al., 2014), again showing how the internal hormonal environment can influence this transition from play fighting to adult aggression. AAS also increased expression of the rate-limiting enzyme for GABA in the AH, VLH, and MeA (Grimes et al., 2003). Furthermore, the precursor to GABA, glutamic acid decarboxylase-65 (GAD65), has also been implicated in the amplification of aggression in rodents across development (Grimes et al., 2003). Excitatory inputs also have a role in AAS-induced aggression. AAS increased fos/glutamate activation in the LAH, decreased afferent innervation from the LAH to the ventrolateral hypothalamus (VLH), and increased vesicular glutamate transporter 2 (VGLUT2) expression in the LAH, suggesting that alteration to excitatory inputs in this region during adolescence may also facilitate adult aggression (Carrillo et al., 2009, 2011). Furthermore, aggression can be increased when glutamate signaling is chronically blocked in a ketamine reduced aggression model of early-life stress (Shin et al., 2019). Overall, these studies suggest that overexpression of both GABA and glutamate are associated with increased adolescent aggression.

Dopamine (DA)

Dopamine is a neurotransmitter known for its role in reinforcing behavior, including the appetitive aspects of adolescent aggression. Optogenetic activation of DA neurons in the VTA, an area known for its role in reward, increases aggression (Yu et al., 2014). Furthermore, blocking DA during the peri-adolescent stage (but not early postnatal development or adulthood) in mice increased aggression in adults, consistent with at least some other findings that there is a link between experiences influencing DA during development and adult aggression. For example, experiences with stress and social defeat can significantly impact the development of the DA system. Social defeat in adolescent male rats decreased prefrontal cortex (PFC) DA function in adults (Watt et al., 2009). This effect is likely controlled by increased clearance of DA via the DA transporter that decreases the amount of DA in the synapse (Novick et al., 2015). In mice, early-life stress in preadolescents enhanced postsynaptic response to excitatory inputs, leading to aberrant plasticity in the PFC, and increased aggression. This phenotype was rescued by systemic D1 antagonists, suggesting D1 receptors may play an important role in mediating this increased aggression (Frau et al., 2019). As the PFC is an important area for regulating the mesolimbic DA and inhibiting appetitive aggression, dysregulation of this system may predispose individuals to maladaptive aggression (Tielbeek et al., 2018). Additionally, several studies on AAS treatment during adolescence have shown that stimulation of the DA system increases aggressive behavior. In golden hamsters AAS treatment during adolescence increased DA production in the AH, specifically the nucleus circularis and medial supraoptic nucleus as well as increasing D2 receptor levels, but not D5 receptor levels, in the AH and ventrolateral hypothalamus (VLH; Ricci et al., 2009; Schwartzer & Melloni, 2010b). Blocking D2 receptors in the AH during AAS treatment suppressed aggression in treated animals (Schwartzer & Melloni, 2010a). In short, activation of the DA system appears to generally have a stimulatory effect on aggression during adolescence.

Vasopressin (AVP) and Serotonin (5HT)

AVP has long been implicated in the control and development of aggression. For instance, AVP, especially that found in the AH, has been implicated in the control of the play-fighting, which may be a precursor to aggression (Cheng et al., 2008). Genetic knockouts of one AVP receptor subtype, V1b, resulted in the suppression of agonistic behavior in adult mice (Wersinger, Caldwell, Christiansen, et al., 2007), although surprisingly, there was no change in agonistic behavior in V1a receptor knockout mice (Wersinger, Caldwell, Martinez, et al., 2007), a receptor type commonly associated with aggression. In hamsters, the development of the AVP system is linked to the onset of adult aggressive behavior (Cheng et al., 2008). Early-life AVP injections in prairie voles resulted in adult increases in aggressive displays (Stribley & Carter, 1999). A similar effect was found in male rats that experienced early-life maternal separation; amount of offensive play-fighting was increased and associated with increased AVP mRNA in the PVN and BNST (Veenema & Neumann, 2009). Additionally, early-life manipulations increasing paternal retrievals in the monogamous California mice, increased AVP immunoreactivity in the BNST and was associated with decreased attack latency (greater aggressive motivation) in resident-intruder tests in both female and male offspring (Frazier et al., 2006). These studies suggest AVP plays an important role in how rodents develop aggressive tendencies and display early agonistic behavior.

Serotonin, another neurotransmitter, likely inhibits aggression by dampening the AH-AVP neurons that normally increase aggression (Ferris, 2000). In the context of development, the serotonin system changes throughout puberty, and its influence on the hypothalamus appears to impact agonistic behavior (Cheng et al., 2008). The relationship is, however, complex, and lifelong reductions in serotonin effects, by using serotonin transporter knockout rats, were found to reduce juvenile social play (Homberg et al., 2007). For lifelong manipulations it is unclear whether compensatory mechanisms activate to adjust for the many behaviors influenced by serotonin. Similarly, blocking serotonin in mice during peri-adolescence reduced adult aggression, and blockade prior to peri-adolescence primarily increased anxiety and depression-like phenotypes in mice (Yu et al., 2014). The impact of selective serotonin reuptake inhibitors (SSRIs) on agonistic behavior also changes across puberty, with low doses of the SSRI fluoxetine resulting in an increase in agonistic behavior in pubertal hamsters but an inhibition of agonistic behavior in adults. Similarly, in mice, prepubertal exposure to SSRIs increased aggression (Svirsky et al., 2016). Furthermore, the same investigation evaluated the change in serotonin innervation across age and found that there is increased serotonergic presence in the AH in adult hamsters when compared to pubescent hamsters (Taravosh-Lahn et al., 2006). As such, serotonin is theorized to be related to the transition of play-fighting behavior into adult aggression, as well as the inhibition of aggression in adults.

The serotonin system also influences appetitive aspects of adolescent aggression as shown by studies that manipulated AAS and cocaine-seeking. AAS-treated adolescent hamsters typically show higher levels of aggression and have lower levels of serotonin receptor 1A (5-HT$_{1A}$) immunoreactive staining in the AH, VLH, and MeA (Grimes & Melloni, 2002; Ricci et al., 2006), but the behavioral effects can be reversed with 5-HT$_{1A}$ receptor activation (Ricci et al., 2006). Similar to AAS administration during adolescence, cocaine exposure during adolescence also facilitates offensive aggression and reduces serotonin expression in the AH, LS, MeA, and BNST (DeLeon et al., 2002). Treatment with SSRIs blocked the cocaine-induced increase in aggression (DeLeon et al., 2002) and this effect is likely controlled by 5-HT$_3$ and 5-HT$_{1A}$ receptor activation (Knyshevski et al., 2005; Ricci et al., 2004). Overall, there is strong evidence for serotonin inhibiting aggression during stages of development and as adults.

Oxytocin

Oxytocin (OXT) is a neuropeptide that differs from AVP by two amino acids and is often found in similar brain regions (Smith et al., 2019) and the two neuropeptides can bind to each other's receptors. In aggressive rats, adolescent treatment with OXT increased attack latency, suggesting that OXT may attenuate aggressive response (Kozhemyakina et al., 2020). However, other studies have found a positive association between OXT and expression of play and aggression. In mandarin voles, paternal deprivation decreased play fighting and number of OXT immunoreactive cells in the PVN, suggesting that OXT in the PVN may play an important role in promoting juvenile social play (Wang et al., 2012). Similarly, in female and male rats, post-weaning isolation increased aggression and upregulated OXT mRNA in the PVN but decreased OXTR expression in the NAc (Oliveira et al., 2019). Together, these studies suggest that altering the OXT system may have variable effects on the expression of aggression based on species, and the function of OXT in the different brain regions is not clear. Across development, OXTR expression changes in several areas known for their role in aggression: OXTRs increase in the PFC, MeA, BNST and VMH from the juvenile period to adulthood, but decrease in the LS (Dumais & Veenema, 2016; Smith et al., 2017). This suggests that changes to the OXT system may be responsible for age-dependent differences in aggression.

Maternal Aggression

From an ecological perspective, we focus on maternal aggression as a means to defend young offspring (Erskine et al., 1978; Rosenblatt et al., 1994) through attack behavior and threat displays. Such aggression can be fierce as pups are defended against predators and intruding males and females and a dramatic difference can be observed between postpartum and virgin females. This definition encompasses maternal aggression as a mechanism for increasing offspring survival. Maternal aggression is often critical in rodents to protect against infanticide from conspecifics (Wolff, 1985), hence, for example, the strong difference in responses of mothers to scents of the father compared to scents of unfamiliar males (Breedveld et al., 2019). Mothers will display increased time at the nest and greater vigilance in response to the unfamiliar males, echoing the response that is seen when exposed to predators of other species. We also touch briefly on how understanding neuroendocrine control of rodent aggression (Lonstein & Gammie, 2002) can help us to understand human aggression, but also the implications of manipulating these neuroendocrine compounds in humans. For neuroendocrine control of maternal aggression, we focus on how rodents are influenced by serotonin, the neuropeptides oxytocin (OXT) and vasopressin (AVP), and corticotropin releasing factor (CRF). We then briefly touch on other neuroendocrine compounds.

Serotonin

An understanding of the effects of serotonin and maternal behavior is important from a human perspective because of the use of serotonin reuptake inhibitors for treatment of postpartum depression in humans (Lonstein, 2019; Ramsteijn et al., 2020). Recent research on the role of serotonin in the control of maternal aggression has resulted in exciting advances, as summarized by Pawluski et al. (2019). The circuits are complex; the effects can be both inhibitory and excitatory and highly dependent on which area of the brain is involved. We summarize the brain regions implicated in serotonin effects on maternal aggression in rodents, particularly regions in which serotonin receptors, 5-HT$_{1A}$ and serotonin receptor 1B (5HT$_{1B}$) receptors, have been targeted in Table 1. Evidence suggests that 5-HT$_{1A}$ receptor activation of the median raphe nucleus (MnR), anterior corticomedial amygdaloid nucleus (ACoM) and dorsal periaqueductal gray (DPAG) dampens maternal aggression, while the medial septum (MS) stimulates maternal aggression (De Almeida & Lucion, 1997). The stimulatory effects of 5-HT$_{1A}$ receptor activation in the DNR further supports the role of the raphe nucleus in stimulating aggression via 5-HT$_{1A}$ receptors (see Table 1). Included in this research is a recent study that elegantly targeted the dorsal raphe nucleus (DRN) with serotonin-specific lesions during midprepartum and early postpartum (Holschbach et al., 2018); these manipulations significantly reduced maternal aggression. Moreover, the decrease in serotonin immunoreactivity in the dorsomedial raphe nucleus (DRdm) was accompanied by a decrease in the AH, a brain area associated with serotonin and aggression in male rodents (Ricci et al., 2006), as well as AVP and aggression in males (Ferris & Potegal, 1988). A

Table 1

Brain Region Specific Effects of Serotonin Manipulations on Maternal Aggression With a Focus on 5-HT$_{1A}$ and 5-HT$_{1B}$ Serotonin Receptors

Species	Brain region	Technique/Treatment	Aggression	Link with aggression
Rat	MnR	5-HT$_{1A}$ receptor agonist[a]	D	negative
Rat	ACoM	5-HT$_{1A}$ receptor agonist[a]	D	negative
Rat	DPAG	5-HT$_{1A}$ receptor agonist[a]	D	negative
Rat	MS	5-HT$_{1A}$ receptor agonist[a]	I	positive
Rat	VO-PFC	5-HT$_{1B}$ receptor agonist[b]	D	negative
Rat	DRdm	serotonin-specific lesions[c]	D	positive
Rat	DRN	5-HT$_{1A}$ receptor agonist[d]	I	positive
Rat	VO-PFC	5-HT$_{1B}$ receptor agonist[d]	D	negative
Rat	DRN*	5-HT$_{1A}$ receptor agonist[d]	D	positive
	VO-PFC	5-HT$_{1B}$ receptor agonist[d]		
	VO-PFC	5-HT$_{1B}$ receptorantagonist[d]	I	negative

Note. Results are integrated in the text above. the aggression column refers to an increase (I) or decrease (D) in aggression in response to the treatment and the link with aggression column refers to either a negative or positive association between the endocrine compound and the level of aggression

[a] De Almeida and Lucion (1997).

[b] Veiga et al. (2007).

[c] Holschbach et al. (2018).

[d] da Veiga et al. (2011).

* Each brain region is injected with the associated agonist at the same time.

number of brain areas have been associated with maternal aggression, but this connection between the DRN and anterior hypothalamus may prove to be particularly important, as this research also separates aggression and anxiety. Finally, the ventro-orbitofrontal prefrontal cortex (VO-PFC) via the 5-HT$_{1B}$ receptors appears to have an inhibitory effect on maternal aggression via the DRN. Overall, the results suggest activation of maternal aggression via 5-HT$_{1A}$ activation can potentially be inhibited through activation of 5-HT$_{1B}$ receptors. Such findings have potential implications for treatment of postpartum depression because of the need for understanding natural changes in the serotonin system that occur during the postpartum period (Lonstein, 2019).

Oxytocin (OXT) and Vasopressin (AVP)

Results for the effects of the neuropeptides OXT and AVP on maternal aggression are more mixed; signaling by both have been linked to maternal aggression; links with anxiety appear to mediate some of the effects; and AVP acts through both receptor types. OXT infused into the central amygdala (CeA; an area of the amygdala associated with stress) increased number of bites toward male intruders in golden hamster mothers (Ferris et al., 1992). Maternal experience may be necessary for this effect because in golden hamsters, virgin females showed decreased aggression after OXT treatment to the medial preoptic-anterior hypothalamic continuum (Harmon et al., 2002; see also serotonin section for connection of the anterior hypothalamus with aggression). The difference may also lie in a switch between other types of aggression (defensive or offensive) and maternal aggression.

A rat model has been developed for examining high and low anxiety mothers (Neumann et al., 2010) with high anxiety mothers exhibiting a very protective mothering style (Bosch, 2013). This approach is grounded in findings that when high anxiety females are tested in a maternal defense test, they have higher levels of stress hormones (Douglas et al., 2007). High anxiety mothers display more defensive aggression toward intruders, more OXT release in the PVN and CeA, but no differences in mRNA levels of OXT receptors compared to low anxiety mothers (Bosch et al., 2005). This indicates that OXT release may drive this type of behavioral variation rather than differences based on receptor characteristics. In addition, expression of brain activity markers such as c-Fos and EGR-1 is greater in another brain area, the amygdala, following aggression; OXT antagonists in the CeA reduce maternal aggression in high anxiety mothers (Bosch et al., 2005; Gammie & Nelson, 2001; Hasen & Gammie, 2006). Bosch et al.(2005) also found that the OXT antagonist in the PVN reduced maternal aggression in these high anxiety mothers. Another study did not replicate these findings (Consiglio et al., 2005). Overall, however, it appears that OXT in the PVN may be regulating activity in the amygdala, but the PVN and CeA cannot explain all of the variability in the literature (summary for manipulations in Table 2). Two other areas of interest are the bed nucleus of the stria terminalis (BNST; Consiglio et al., 2005) and the medial prefrontal cortex (mPFC).

Results for AVP overlap with OXT to some degree and have been well reviewed (Klampfl et al., 2018). Both the anxiety model and unselected lines have been used to investigate AVP and maternal aggression. High and low anxiety selected lines often respond differently to the neuropeptide manipulations (see Table 2). It is interesting that this behavioral anxiety rat model appears to be based on a polymorphism in the promoter region of the AVP gene (Murgatroyd et al., 2004), this may explain some of the variation that occurs when comparing different models. Also of interest is the finding that AVP and OXT bind to receptors of both of these neuropeptides (Song & Albers, 2018) and some effects may be a balance of activation of the receptors from the two neuropeptides. Moreover, it is also important for us to recognize that OXT has one receptor type, whereas AVP has two types; the V1a receptor (V1aR) has received the most attention for impact on that influence social behavior but the V1b receptor also influences aggression in males (Wersinger, Caldwell, Christiansen, et al., 2007; see Table 2).

Intracerebroventricular administration of AVP reveals that maternal aggression is decreased via AVP and increased via an

Table 2

Examples of Brain Region Specific Effects of Oxytocin (OXT) Followed by Vasopressin (AVP) Manipulations on Maternal Aggression

Species	Brain region	Treatment	Treatment effect on aggression	Link with aggression
Rat (high anxiety)*	PVN	OXT-antagonist[a]	D	positive
Rat (low anxiety)*	PVN	OXT[a]	I	positive
Rat (high anxiety)*	CeA	OXT-antagonist[a]	D	positive
Rat	CeA	OXT[b]	D	negative
Rat	BNST	OXT[b]	D	negative
Rat	mPFC	OXTR-antagonist[c]	I	negative
Golden hamster	CeA	OXT[d]	I	positive
Rat	BNST	V_{1A}-antagonist[e]	D	positive
Rat (high anxiety)*	CeA	V_{1A}-antagonist[f]	D	positive
Rat (low anxiety)*	CeA	V_{1A}-antagonist[f]	I	negative

Note. Only results for $V1_A$ receptors are summarized. See Bosch and Neumann (2012) and Bridges (2015) for a more detailed analysis of the association between these neuropeptides and maternal aggression. The aggression column refers to an increase (I) or decrease (D) in aggression in response to the treatment and the link with aggression column refers to either a negative or positive association between the endocrine compound and the level of aggression.

[a] Bosch et al. (2005).

[b] Consiglio et al. (2005).

[c] Sabihi et al. (2014).

[d] Ferris et al. (1992).

[e] Bosch et al. (2010).

[f] Bosch and Neumann et al. (2010).

* The difference between high anxiety mothers may have reached a maximum threshold, whereas low anxiety mothers may have reached a minimum threshold for maternal aggression activated through OXT and AVP.

AVP receptor antagonist (Nephew et al., 2010; Nephew & Bridges, 2008). This is consistent with many findings that AVP increases aggression in adult males (see section on Male-Male Aggression: Vasopressin). In contrast, V1A knockout mice expressed no change in maternal aggression, or male aggression for that matter, and has been interpreted to be a result of lifelong compensation for the lack of V1A receptors (Wersinger, Caldwell, Christiansen, et al., 2007). Temporary gene knockouts will be needed in adults to test the effect of V1A knockouts or repression to examine this more closely. V1b receptor knock-outs in mice had a more expected result which was decreased maternal aggression, similar to findings of aggression in males (Wersinger, Caldwell, Christiansen, et al., 2007). For brain specific regions, similar to OXT and the anxiety model, blocking vasopressin (V1a) receptors in the CeA also increased maternal aggression in low anxiety mothers but decreased it in high anxiety mothers (Bosch & Neumann, 2010). In a nonselected line, the BNST appears to be another brain region involved in regulation of maternal aggression such that a selective V1a receptor antagonist decreased maternal aggression (Bosch et al., 2010). Vasopressin again has more than one receptor type; it is worth noting that using a V1b antagonist in the medial posterior BNST had no effect on maternal aggression, suggesting that only V1A receptors in the BNST are important for maternal aggression (Klampfl et al., 2016).The emerging picture is again that the effects of AVP on maternal aggression depend on brain area and possibly level of anxiety, although there is evidence that the positive association between AVP and aggression in males can be found in maternal aggression as well.

Corticotropin Releasing Hormone (CRF)

Thus far, this review of maternal aggression shows that serotonin, OXT and AVP have proven to be critical for modifying maternal aggression, but evidence suggesting the role of anxiety based defense leads to the investigation of the stress axis and, in this case, CRF is particularly important as it generally inhibits both maternal aggression and maternal behavior. For example, intracerebroventricular injections of CRF inhibit maternal aggression (Gammie et al., 2004). If the bonding protein for CRF is knocked out, mice selected for high levels of maternal anxiety also exhibit decreased maternal aggression (Gammie et al., 2008), thus higher aggression is associated with down regulation of the stress axis. LS is a gateway for the effects of stress and is involved in regulating the inhibitory effects of CRF on both maternal aggression and maternal behavior (Gammie et al., 2009). The importance of CRF is further supported by the finding that CRFR2-deficient mice display a deficit in maternal aggression. As an aside, the idea of the LS as being important for maternal aggression is further supported by findings that stimulation of GABAA receptors in LS enhances maternal aggression whereas inhibition of this receptor decreases aggression. More recently both the BNST (Klampfl et al., 2016, 2018) and MPOA (Klampfl et al., 2018) have been linked to the negative impacts of CRF on maternal aggression through receptor studies (CRFR1), as well as binding proteins.

Other Neuroendocrine Compounds

A number of other neuroendocrine compounds and hormones have been investigated and we briefly touch on some of these. As reviewed by Lonstein and Gammie (2002), ovarian hormones have been investigated and estrogen enhances maternal aggression, but changes in progesterone appear to be less important for maternal aggression. One mechanism through which testosterone can influence behavior is via conversion to estrogens through the enzyme aromatase. Using a gene targeting strategy to isolate aromatase positive neurons in specific brain regions, it has also been demonstrated that aromatase in the medial amygdala in both male and female house mice influenced aggression, albeit specifically maternal aggression in females (Unger et al., 2015). Moreover, if an antagonist to gonadotropin releasing hormones is administered, this decreases maternal aggression (Bayerl et al., 2019). The Gammie lab, using the aggression selected lines they developed, found that neurotensin impairs maternal aggression (D'Anna & Gammie, 2009), along with Urocortin 1 and 3 (related to CRF; D'Anna & Gammie, 2006). Activation of mu opioid receptors also inhibits maternal aggression (Lambert & Byrnes, 2019). Depending on dose, hypocretin-1 modulates maternal aggression (D'Anna & Gammie, 2006). More compounds that influence maternal aggression are likely to be identified.

Summary of Maternal Aggression

The control of maternal aggression appears to be a balance of neurochemicals that incorporates a drive toward maternal aggression but that also includes breaks on maternal aggression such as through stress. Chronic early life stress is another perspective from which associations between neuroendocrine compounds and maternal aggression can be examined; stress can decrease maternal aggression. Stress is one of the ways in which to examine maternal aggression, but other approaches have proven fruitful as well. There are a number of neural nodes involved in this complex inhibitory and stimulatory control of maternal aggression that includes classical components of the social neural network and other brain regions such as the amygdala, BNST, mPOA, PVN, components of the raphe nucleus, mPFC, dorsal and lateral septum.

Adult Male-Male Aggression

Adult male-male aggression is displayed when there is competition for resources such as mates, shelter, and food (Scotti et al., 2015; Soma et al., 2015) and often spaces out males when there are resources to defend. The establishment of a territory is therefore important for securing resource access, and male-male aggression is an important method of territory establishment and defense at the risk of energy expenditure, injury, and time, as well-reviewed elsewhere (Duque-Wilckens et al., 2019). Since physical altercation with another male can be costly, rodents engage in a number of behaviors to broadcast territorial information in order to avoid physical conflict. Odor cues to scent-mark territory are commonly used, though some rodents will vocalize to avoid physical aggression (Banerjee et al., 2019). The display of submissive postures or ritualized fighting are other mechanisms by which rodents avoid physical encounters (Soma et al., 2008). Regardless, the males of many species readily engage in aggressive physical altercation when faced with a same-sex territorial intruder (Scott, 1966). Therefore, territorial aggression is most frequently studied using the resident-intruder test, in which a focal animal is allowed to establish a residency in a testing chamber, after which an unfamiliar male is introduced.

Social structure, too, may determine the implementation of male-directed aggression. Highly social rodents, such as the rat, may live in groups with multiple males and may therefore selectively display territorial aggression to outgroup males. However, in these communities, male-male aggression is important during the establishment and maintenance of dominance hierarchies. Rodent hierarchy-related aggression is less frequently studied than territorial aggression, but is most frequently accomplished with rats using tube tests or ecologically-approximate home cage designs such as artificial burrow systems.

Testosterone

Most mammalian studies on the neuroendocrine mechanisms of male-male aggression have demonstrated that testosterone is required for its display (Trainor et al., 2009). Classic remove-and-replace studies in rodents have revealed that male aggression is reduced by castration and restored by testosterone replacement (Duque-Wilckens et al., 2019; Payne & Swanson, 1972; Sayler, 1970; Soma et al., 2015). Consistent with these findings, aggression-associated brain regions are enriched with androgen receptors (AR), and high concentrations of ARs are present in the adult male mPOA, VMH, AMY, NAc, BNST, and septum (Fernandez-Guasti et al., 2003.; Lu et al., 1998; Simerly et al., 1990; Wood, 1995; Zheng et al., 2021). Male mice with mutant AR do not engage in physically aggressive behavior (Juntti et al., 2010), and pharmacological studies also indicate a role for this receptor in controlling aggression (Finney & Erpino, 1976; Sato et al., 2004; Wallis & Luttge, 1975).

While male-male aggression has historically most often been associated with serum testosterone, recent studies have observed that long-term baseline serum testosterone levels do not always correlate well with aggressive behavior (Caldwell et al., 1984; Duque-Wilckens et al., 2019; Trainor & Marler, 2001). This is likely because serum testosterone can be converted into DHT, a potent androgen, or estradiol, an estrogen, once it reaches the brain. Moreover, testosterone can be synthesized directly in the brain from the precursor DHEA (Soma, 2006). Thus, metabolism and synthesis of testosterone in the brain is often more important for understanding testosterone effects on behavior than serum testosterone (Duque-Wilckens et al., 2019). In line with this, short hairpin RNA (shRNA) knockdown of ERα in the rat VMN in adulthood reduced aggressive behavior, indicating the testosterone-related aggression requires expression of ERα in the VMN (Sano et al., 2013).

The social context of the aggressor is also important for androgen-facilitated aggression. The presence of an estrous female increases testosterone-dependent aggression in the rat (Taylor et al., 1984). Similarly, castrated male Mongolian gerbils with testosterone replacement that also cohabitated with a female displayed aggression toward an unfamiliar male, while those that cohabitated with a male instead of a female did not (Piña-Andrade et al., 2020). Collectively, this would indicate that female presence is a social context that modulates the expression of testosterone-dependent territorial aggression.

Beyond social context, prior aggressive experience and location are also important for regulating the dynamic effects of androgens on aggression (Gleason et al., 2009). Manifested in the winner effect, repeated winning causes an increase in aggressiveness and can be critically dependent on a postwinning testosterone surge (Lipshutz et al., 2019; Marler & Trainor, 2020; Moore et al., 2020). These testosterone surges have been studied extensively in California mice (Oyegbile & Marler, 2005b). In this same species, a robust winner effect emerges only after winning aggressive bouts in the home territory (Fuxjager et al., 2010) and a maximum ability to win emerges with a combination of winning experience in the home territory and postencounter surges in testosterone (challenge effect; Fuxjager et al., 2011; Gleason et al., 2009). AR sensitivity in NAc and VTA, key regions involved in motivation and reward, increases only in response to fights won in the home territory, while sensitivity in maBNST increases regardless of location.

A caveat to add to the above discussion and as described in several reviews is that there is variability among species with regard to both testosterone levels and the relationship between testosterone and aggression (Goymann et al., 2019; Moore et al., 2020) such as climate (Husak et al., 2021). It is clear from these reviews and others that the challenge effect is being extended to incorporate plasticity in response to environmental cues and life history (Marler & Trainor, 2020; Rieger et al., 2018).

Estrogen

Estrogen has important effects on male aggression, and while the majority of research has investigated the role of estrogen receptors in male-typical development, such as in ER knockout studies (Ogawa et al., 1997; Scordalakes & Rissman, 2003), there is evidence that estrogen receptors in adulthood are also important for male aggression. Estrogen manipulation studies indicate that estradiol increases the likelihood of male-male aggression in resident-intruder tests (Simon, 2002), and in CD-1 mice, levels of male-male aggression were positively correlated with the number of ERα-immunopositive cells in the LS, BNST, and AHA (Trainor et al., 2006). However, estrogen-induced increases in aggression appear to be context-dependent (Trainor et al., 2004). It is likely that differences in aromatase enzyme activity, estrogen receptor subtype expression, and nongenomic effects have important effects on estrogen-mediated aggression in male adults (Trainor et al., 2008).

Oxytocin (OXT)

Evidence points toward the involvement of the OXT system in regulating aggression in rodents. In general, reduced expression of OXT or lower activation of OXT neurons is associated with higher aggression (de Jong & Neumann, 2018), while greater OXT signaling is associated with decreased aggression (Hathaway et al., 2016). Accordingly, low-aggressive male rats express more OXT mRNA in the PVN compared to males that are highly aggressive (Calcagnoli et al., 2014). While intranasal (Calcagnoli et al., 2015) and central (Calcagnoli et al., 2014, 2015) infusion of OXT has been shown to reduce male-male aggression in rats, a firm understanding of circulating OXT dynamics remains somewhat elusive. In some species, OT has no effect on adult male-male aggression. For example, increased activation of the OXT system in prosocial encounters is not well reflected in increased plasma levels of OXT (Trainor et al., 2009).

A number of studies have investigated OXTR binding in aggression-related regions (see Figure 1; Trainor et al., 2009). Relative to low-aggressive males, highly aggressive male rats have increased OXTR binding in CeA, BNST, and mPOA and decreased binding in the caudate putamen and LS (Calcagnoli et al., 2014; Lukas et al., 2010). However, patterns of OXT receptor binding differ across rodent species (Insel & Shapiro, 1992), and likely impact the behavioral effects of both endogenous and exogenous OXT. A classic example is with the monogamous prairie vole and the nonmonogamous montane vole: male prairie voles, which show a high density of OXT binding in the prelimbic cortex, BNST, NAc, and lateral amygdala, become aggressive toward male intruders after forming a pair bond, while the montane vole shows much lower OXT binding in these regions and is much less aggressive (Ferris, 2005). Virgin males of both species show little change in aggression following ICV (intracerebroventricular injections) administration of OXT (Winslow et al., 1993), however, following mating, prairie voles become aggressive in response to OXT while montane voles do not. Taken together, it is clear that not only species differences, but also experience-dependent plasticity alter OXT's effects on male aggression.

Vasopressin (AVP)

In contrast to OXT, AVP signaling in the brain is generally considered to facilitate aggression in males. For example, infusion of AVP into AH or VLH of hamsters increased the number of attacks (Caldwell & Albers, 2004; Ferris et al., 1997), and a V1aR antagonist infusion to AH resulted in decreased aggression (Ferris & Potegal, 1988). The AH has been repeatedly linked to the control of aggression in select rodent species (for review see Nelson & Chiavegatto, 2001). Latency to bite the intruder also increased, indicating perhaps a reduction in appetitive aggression. Likewise, prairie voles dose-dependently increased their aggression toward an intruder following ICV infusion of AVP (Young et al., 1997) and ICV infusion of V1aR antagonist reduced aggression (Winslow et al., 1993). Moreover, ICV AVP antagonists decreased aggression in male California mice (Bester-Meredith et al., 1999).

Like OXT, however, the role of AVP in aggression is complex, and AVP receptor distribution varies across species. In rats, AVP release in the LS correlated positively with aggression, while AVP release in the BNST correlated negatively (Veenema et al., 2010). In golden hamsters, AVP in the AH stimulated expression of adult male-male aggression (Ferris et al., 1997; Ferris & Potegal, 1988). Increased AH AVP receptor concentration has been associated with increases in aggression in rodent models (Albers et al., 2006). In highly aggressive males, V1aR antagonist infusion into LS decreased aggression, and AVP infusion into BNST likewise decreased aggression. Other studies, however, have found AVP release in LS to correlate negatively with aggression (Everts et al., 1997) but infusion of AVP into amygdala or LS facilitates attack behavior (Koolhaas et al., 1990) or social and anxiety-related behaviors (Beiderbeck et al., 2007). V1aR knockouts have also been used to study the role of AVP in male aggression, however it is difficult to interpret adult behavior from these studies, as developmental compensation is likely to have occurred (Terranova et al., 2017). In contrast to rats the California mouse, a highly aggressive species, has elevated levels of AVP immunoreactivity in the BNST and LS compared to the white-footed mouse, a less aggressive relative (Bester-Meredith et al., 1999). Taken together, it is clear that the region-specific effects of AVP on male aggression can depend on receptor density, although release can also be important.

Testosterone and AVP Interplay

The mechanism by which testosterone regulates aggression is through both androgen and estrogen receptors, but also receptors of a diverse set of neurochemical receptors such as the well-established regulation of V1aR by testosterone. The relationship between testosterone and AVP is expressed in a variety of brain areas; we highlight a few here. Perhaps the most important brain regions include MeA, BNST, and LH. Testosterone implants result in more AVP mRNA-ir cells in the BNST in adult male rats than in females as well as more dense connections from the BNST to LS and the LHb nucleus (e.g., De Vries et al., 1994). An additional layer of control was revealed through methylation of AVP genes through exposure to testosterone (Auger et al., 2011. In both intact and castrated male rats, local infusion of AVP into the medial amygdala resulted in an increase in aggressive behavior (Koolhaas et al., 1990). However, the amount of aggressive behavior declined 6 months following castration, suggesting that the effects of AVP are dependent on testosterone. V1aR expression disappears in LH following castration in male rats, but is maintained with testosterone treatment (De Vries et al., 1994). Injection of AVP into LH did not rescue aggression in castrated males. In summary, it is therefore likely that testosterone facilitates aggression, at least in part, through the activation of AVP in MeA, BNST, and LH.

Serotonin

In contrast to the effects of AVP, serotonin displays an overall inhibitory effect on adult aggression. Serotonin influence from the dorsal raphe (DRN) has been shown to inhibit the display of adult aggression and activation of 5-HT$_{1A}$ receptors in the AH may be particularly important for this effect (Ferris et al., 1999). For instance, in mice, depletion of central serotonin enhanced aggression in isolation-reared mice and application of serotonin in knockout mice inhibited the increased aggression typically observed in isolation-reared mice (Liu et al., 2019). For a more in-depth review of serotonin's actions on aggression see a review by Olivier (2004).

Disentangling Vasopressin and Oxytocin

While it is clear that OXT and AVP are involved in regulating aggression, it is challenging to disentangle the effects that are mediated by oxytocin receptor (OXTR) and those mediated by V1aR, considering the high affinity of each peptide at the other's receptors. This is likely due to OXT being similar in structure to AVP, as well as OXT and AVP receptors being similar in structure to one another (Song & Albers, 2018). Several studies have been able to block some of the antiaggressive effects of OXT using antagonists (Calcagnoli et al., 2013, 2015), however, in many of these studies the antagonists used also affect V1aR. Taken together, it is likely that OXT and AVP can influence aggression by acting on each other's receptors, however this relationship remains to be fully understood (Terranova et al., 2017).

Male-Male Dominance Hierarchies

Most group-living animals develop dominance hierarchies, including some rodent species. Notably, both house mice (So et al., 2015; Williamson et al., 2016) and rats (Blanchard et al., 1988; Opendak et al., 2016) develop dominance hierarchies that are important for the expression of aggression relative to social ranking. Alpha males often exhibit high levels of aggression toward more subordinate males yet rarely receive aggression from subordinates. Subordinate males, on the other hand usually only exhibit aggression toward other subordinate males (So et al., 2015).

Recent evidence has uncovered a role for neuropeptides in dominance hierarchy formation and maintenance. Stress-induced subordinance in male rats showed lower OTR expression in MeA relative to dominant males (Timmer et al., 2011). Local administration of a selective OXT antagonist to MeA in an unstressed subordinate immediately following acquisition of subordinate status reduced the expression of subordination 8 days later. These findings support the hypothesis that OXT signaling and changes in OXTR receptor expression lead to hierarchy position memory maintenance (review by Bielsky & Young, 2004), and that such effects might be regulated by the MeA.

In addition to MeA, peptide receptor binding in other regions has been shown to be associated with male-male hierarchy status. Dominant male mice had higher OTR binding in nucleus accumbens (NAc) core, anterior olfactory nucleus, and rostral LS than did subordinate males (Lee et al., 2019). In contrast, subordinate males had higher V1aR binding in rostral LS and lateral POA. It is becoming more clear that different social experiences within a hierarchy drive patterns of OXTR and V1aR binding; future studies should continue to explore how such changes and the expression of other hormone receptors, such as GnRH (Williamson et al., 2017) lead to the variable expression of aggressive behaviors.

Female-Female Aggression

Steroid Hormones

Neuroendocrine effects on female-female aggression is generally understudied in rodents with the exception of maternal aggression. Two recent reviews of female aggression highlight the need for studying female aggression across species, including humans (Duque-Wilckens & Trainor, 2017). With respect to specific brain areas, Been et al. (2019) provide an excellent summary of steroid hormone manipulations that influence female aggression and implicate brain regions including the VMH, AH, amygdala, medial preoptic area (mPOA), and BNST.

We review a few primary points here. Females also compete for resources and social status which can be critical for obtaining resources for both their survival and that of their young. Moreover, females fight to stop conspecifics from committing infanticide. As an example, monogamous female California mice are highly aggressive outside of the context of maternal aggression such that female-female aggression is very similar to male-male aggression (Rieger & Marler, 2018). Both sexes share and defend a territory with its resources and also spatially exclude conspecifics likely to also prevent infanticide. Neuroendocrine contributions to female-female competition have been gaining attention, but primarily in avian research (Rosvall et al., 2012). A few rodent examples, however, exist, with a primary focus on steroid hormones. The most extensive research involves progesterone control of female aggression. Progesterone reduces aggression when first primed with estrogen, mimicking estrus (Floody, 1983; Goymann et al., 2008; Takahashi et al., 1983). It is interesting that in California mice, there is a transient drop in progesterone following a female-female encounter, possibly releasing an inhibitory effect of progesterone on aggression (Davis & Marler, 2003).

The focus on testosterone in female aggression in birds raises the issue of whether testosterone should be more broadly studied across different species. For females, an important selection factor for testosterone or androgen influences on behavior may be the presence of physiological/neural mechanisms for avoiding the costs of high androgens, but also different mechanisms may be used (Rosvall et al., 2012). Altering responsiveness and location of production of androgens at a tissue level is critical. An excellent example of this is provided by (Bentz et al., 2019) in which competitive female tree swallows were found to exhibit tissue specific changes in enzymes in the liver and ovaries when establishing territories (defending nest boxes) but without apparent changes in regulation from luteinizing hormone (released from the brain to increases testosterone). To our knowledge such peripheral tissue specific studies have yet to be conducted in rodent models with high levels of female aggression.

An interesting mechanism that may have evolved in females, similar to males, to potentially avoid costs of testosterone can occur through steroid production from neural tissues. This avoids release of high levels of hormones that can reach multiple brain regions and peripheral tissues. A useful rodent model system has been Siberian hamsters in which both sexes are highly aggressive during both the breeding and nonbreeding season. As described below female aggression can be sustained by melatonin, possibly via effects on adrenal androgen dehydroepiandrosterone (DHEA), a prohormone that can be converted to biologically active hormones (testosterone and 17β–estradiol). DHEA is produced in the brain and can influence aggression, although more direct studies are needed to elucidate the mechanisms through which DHEA produced in the brain influences female aggression.

Some rodents, such as house mice, form social hierarchies. One study revealed that aggression in female hierarchies (that express less hierarchical linearity than in males) was not associated with female estrus state or estradiol level. Subordinate females, however, had higher corticosterone levels, and higher mRNA for estrogen (ERα, ERβ) and OXT receptors (Williamson et al., 2019).

Oxytocin (OXT) and Vasopressin (AVP)

We previously described how both OXT and AVP modulate maternal aggression, but we can also gain insights into OXT and AVP effects on behavior by investigating nonmaternal aggression. For example, Oliveira et al. (2021) highlights the role of the septum in female aggression that combines OXT and AVP in both the dorsal and ventral lateral septum. The researchers very elegantly demonstrate that female aggression is influenced by a balance between AVP and OXT that is mediated via GABA neurotransmission (inhibitory effects through the dorsal lateral septum) through a balance between the lateral and dorsal subregions of the lateral septum.

In contrast to males, it is also interesting that within dominance hierarchies, female aggression is negatively associated with activation of V1A, OXT and $5HT_{1A}$ receptors (Grieb & Lonstein, 2021). Such results suggest that female-female aggression can be controlled by very different mechanisms and may contribute to the less linear hierarchical structure of female social groups.

In summary, there is evidence for neuroendocrine control of female-female aggression through steroid hormones and neuropeptides and there are similarities between male and female neural aggression networks (D'Anna et al., 2005). Few studies, however, have used the recently developed tools for precise neuroendocrine manipulations in targeted brain nuclei that have been conducted in males. More studies examining GABA and balances of excitatory and inhibitory networks (e.g., Borland et al., 2020; Ferris & Potegal, 1988; McDonald et al., 2012) and hormonal interactions, such as those described in Oliveira et al., 2021; would help to understand the complex balance of control of aggression that results in an adaptive or maladaptive response.

Seasonal Aggression

The fitness of an individual relies on a careful balance between energy investment in survival and reproduction. As seasons change, resource availability may be drastically altered in certain environments, requiring native species to adjust their distribution of energy toward reproduction and survival. Vertebrates have developed species-specific adaptations that involve seasonal changes in reproduction, aggression, body mass, adiposity, foraging, gut efficiency, sleep, growth, immune function, cognition, and affect (Prendergast et al., 2002). Photoperiodism, or the determination of day-length, is the biological ability used to obtain information about the time of year; it is used by plants and animals to make seasonal adaptations (Walton et al., 2011).

In contrast to birds which have deep brain photoreceptors that respond to photoperiodic change, mammals rely on melatonin, secreted by the pineal gland, to determine day length (Nakao et al., 2008; Rendon et al., 2020). The suprachiasmatic nucleus (SCN) in the hypothalamus is the major regulator of mammalian circadian rhythms, and receives input from the retina that signals light and dark (Benarroch, 2008). The SCN sends information downstream to the pineal gland, which increases secretion of melatonin in the absence of light but the SCN is typically not included in studies of social behavior because it is generally not considered to be a part of the neural social circuit (Benarroch, 2008). Melatonin levels have an extended peak at night, and the duration of the peak is inversely correlated with day-length; therefore, the duration of melatonin secretion increases during the winter months (Walton et al., 2011).

During the winter months when resources are more limited and temperatures are low, animals tend to dedicate more energy to survival rather than reproduction (Walton et al., 2011). Aggression is a social behavior often crucial for survival as animals compete for limited resources and defend their territory (Munley et al., 2021). Because of the relationship between steroid hormones and aggression, the alteration or maintenance of aggression from the reproductive to nonreproductive seasons is of particular interest (Duque-Wilckens et al., 2019). Early studies tied a direct link to changes in aggression across the seasons and alterations in levels of testosterone, but newer findings contradict this approach, as some species, such as the wood rat (*Neotoma fuscipes*), continue display seasonal changes in aggression following castration, while other species, such as the Siberian hamster, show increased aggression during the nonreproductive season despite reduced testosterone levels (Caldwell et al., 1984; Munley et al., 2020). Since the discovery that there is not a complete direct link between testosterone and aggression, newer research has evaluated the complex neuroendocrine control of aggression as it changes across the reproductive and nonreproductive seasons.

Melatonin

Levels of aggression increase in some rodent species during the short-day, nonreproductive season, and current evidence suggests that melatonin drives this increase in aggression during the winter months. Male and female Siberian hamsters (*Phodopus sungorus*) increase aggressive behaviors during the short-day condition, or during the long-day condition with timed subcutaneous melatonin injections that mimic short-day melatonin levels (Munley et al., 2020; Rendon et al., 2020). A short-day photoperiod and timed subcutaneous melatonin injections in a long-day photoperiod used to mimic the short-day condition also increase aggression in male golden hamsters (*Mesocricetus auratus*) and California mice (*Peromyscus californicus*); photoperiod has also been shown to influence the behavioral response to hormonal changes, as AVP increases aggression in golden hamsters housed in long-day photoperiods, but not in short-day photoperiods (Caldwell & Albers, 2004; Jasnow et al., 2002; Laredo et al., 2014; Silva et al., 2010). However, the mechanism by which melatonin increases aggression has yet to be fully understood.

One proposed model of melatonin's impact on aggressive behavior is through a change in the regulation of aggression from the gonads in the summer to the adrenal glands in the winter (Munley et al., 2018). Female Siberian hamsters in the "short-day" photoperiod and the females in "long-day" photoperiod given timed melatonin injections experienced gonadal regression, reduced circulating estradiol, and an increase in dehydroepiandrosterone (DHEA) and aggressive behavior, measured using the resident-intruder paradigm (Rendon et al., 2020). A previous study from this same lab showed elevated serum DHEA as well as elevated total DHEA content in the adrenals of female Siberian hamsters following ten weeks of exposure to a short day photoperiod compared to a long day photoperiod (Rendon & Demas, 2016). Aggressive encounters reduced DHEA and serum testosterone in female Siberian hamsters given timed melatonin injections, but not in "short-day" females that were not given timed injections, or in "long-day" females (Rendon et al., 2020). Estradiol in all groups increased following an aggressive encounter, but in "long-day" females, no drop in DHEA and serum testosterone was found (Rendon et al., 2020).

DHEA is released from the adrenals, but can cross the blood–-brain barrier where it is converted by the enzyme aromatase into the biologically active neurosteroids testosterone and estradiol (Beck & Handa, 2004). Therefore, it is possible that melatonin maintains aggressive behavior in the absence of steroid hormones released by the gonads by increasing the release of DHEA during the nonreproductive season (Rendon et al., 2020). The drop in DHEA and subsequent increase in estradiol following an aggressive encounter in females given timed melatonin injections implicates a more significant role of neural aromatase in aggression during the nonreproductive season (Rendon et al., 2020). Further research is necessary, but the PAG and PVN may be the brain areas responsible for the seasonal regulation of aggression through melatonin, as "short-day" females and females given timed melatonin injections to mimic short days displayed a relationship between aromatase cell density in the PAG and paraventricular (PVN) and aggression that was not present "long-day" females (Rendon et al., 2020).

Consistent with the proposal that the adrenals are responsible for the control of aggression during the nonreproductive season, adrenalectomized male Siberian hamsters did not exhibit an increase in aggression associated with melatonin administration, whereas their intact counterparts increased aggressive behavior with melatonin administration (Demas et al., 2004). However, the impact of melatonin on DHEA secretion may only be one way in which it exerts control over seasonal behavioral changes.

Oxytocin (OXT) and Corticotropin-Releasing Factor (CRF)

Melatonin also influences OXT release in certain brain regions, and may be stimulating or inhibitory depending on the concentration. In the Wistar rat (*Rattus norvegicus domestica*) hypothalamo–neurohypophysial system, melatonin increased OXT secretion at higher concentrations and inhibited OXT release at lower concentrations (Juszczak et al., 2016). Melatonin has also been found to inhibit OXT release in the neurointermediate lobe of the golden hamster (Juszczak et al., 1995). As OXT plays a role in the regulation of mammalian social behavior including social approach, social reward, aggression, and communication, seasonal changes in melatonin concentration may alter social behaviors through OXT (Albers & Bamshad, 1998; Arakawa, 2021; Hung et al., 2017; Lukas et al., 2011). However, there are also crucial species differences in seasonal aggression.

Although the majority of work on photoperiodism in mammals has been done on Siberian and golden hamsters, distinct changes in aggressive behavior across the seasons have been observed in other species, such as the meadow vole. Meadow voles (*Microtus pennsylvanicus*) display reduced aggression and increased social behavior during short days, and the normally solitary species form group nests to conserve heat (Lee et al., 2019; Parker et al., 2001). While it may be adaptive for some species to increase aggression during the winter months to protect limited resources, it is adaptive for others to share resources and reduce energy expenditure on thermoregulation (Parker et al., 2001). This stark difference between Siberian hamsters and meadow voles suggests that the generalizability of data on the impact of melatonin on behavior from Siberian hamsters to other species may be limited.

OXT and CRF may both play a role in the seasonal changes in social behavior of meadow voles. Oxytocin receptor (OTR) density is greater in the lateral septum and central amygdala (CeA) in female meadow voles during the short day photoperiod, when the species engages in same-sex affiliation and reduced levels of aggression (Beery & Zucker, 2010). CRF$_1$ receptor density is reduced in the PVN in "short-day" female meadow voles compared to "long-day" females (Beery et al., 2014). OXT in the CeA has been found to attenuate the fear response, and have a suppressive effect on the HPA axis, whereas CRF acting on CRF$_1$ receptors activates the HPA axis (Flandreau et al., 2012; Neumann, 2002). Taken together, the reduction in seasonal aggression in meadow voles during the short-day photoperiod may be a result of the suppression of the HPA axis, which has been linked to aggression (Walker et al., 2018). Although further research is required on the mechanism by which this shift in OTR and CRF$_1$ density occurs, melatonin is also known to have a suppressive effect on the HPA axis through an unknown mechanism, and may be involved in reducing HPA activity during an extended period of short days (Raghavendra & Kulkarni, 2000).

Serotonin

The physiological and behavioral changes driven by photoperiodism have primarily been studied on rodents, but humans also exhibit seasonal patterns in both aggression and affective state that may be influenced by melatonin and serotonin. For example, there are more personal physical attacks during the summer months compared to winter months, leading some to suggest a relationship between photoperiod and aggression in humans (Lauritsen et al., 2014). Serotonin is the precursor to melatonin, and demonstrates seasonal variation as well as a role in aggression (Abbasi et al., 2016; Praschak-Rieder et al., 2008; Tricklebank & Petrinovic, 2019). Longer days have been associated with increased binding of serotonin 5-HT$_{1A}$ receptors, and shorter days with decreased binding in the cortical and subcortical regions of human brains (Matheson et al., 2015; Spindelegger et al., 2012). In rodents and humans, serotonin shows normal fluctuations in relation to daylength, with sunlight increasing serum levels of serotonin, and the lowest levels of serotonin occurring during the short winter days (Birkett & Fite, 2005; Schulz et al., 2002). However, the relationship between serotonin and aggression is not fully understood.

Monoamine-oxidase-A (MAO-A) is an enzyme responsible for the breakdown of serotonin as well as dopamine and norepinephrine and shows seasonal changes, with cerebral MAO-A density lower in the summer compared to winter (Spies et al., 2018). Genetic variation resulting in lower levels of MAO-A and inhibition of MAO-A and a subsequent increase in serotonin has been associated with increased aggression in rodents, nonhuman primates, and humans (Beach et al., 2010; Ficks & Waldman, 2014; McDermott et al., 2009; Shih et al., 1999; Tricklebank & Petrinovic, 2019). However, MAO-A inhibitors have also been used as antidepressants in humans with no observed increases in aggressive behavior, and chronic treatment of rodents with MAO-A inhibitors results in a decrease in aggression (Tricklebank & Petrinovic, 2019).

The recent finding showing a reduction in MAO-A following bright-light therapy in patients with seasonal affective disorder (SAD) and controls implicates serotonin as a factor in the disorder, however the effect was not specific to patients with SAD, therefore further research is necessary (Spies et al., 2018). SAD is a disorder in humans defined by recurrent depressive episodes occurring in the winter months (Partonen & Lönnqvist, 2012). Similar depressive-like and anxiety-like behaviors can be observed in rodent models during short days, and may be an adaptive response to limited resources to decrease energy expenditure (Pyter & Nelson, 2006; Walton et al., 2011). So although there may be a biological basis for seasonal affective disorder, it is unknown why seasonal changes are more significant for those with SAD, as they do not have abnormal secretions in melatonin (Checkley et al., 1993).

Summary of Seasonal Aggression

Seasonal changes in mammalian behavior vary significantly by species but share the common thread of increasing focus of survival during winter months. Alterations in the hormones mediating control of aggression as well as changes in aggression itself are among the many adjustments that occur seasonally. In mammals, these changes are driven largely by an increase in duration of melatonin secretion during the winter months, and a decrease during the summer months (Walton et al., 2011). Like other mammals, humans also experience seasonal behavior and affective changes, however it is not yet known if these changes are directly caused by changes in photoperiod.

Conclusions and Future Directions

In this review we have outlined aggression, an important and complex aspect of social behavior that occurs across species and contexts. Aggression begins developing early in life, often as social play, as individuals learn how and when to aggress through low-risk play behaviors that evolve into full grown aggression as they reach puberty. Once adulthood is reached aggression is shown across different contexts but one constant across these types of aggression from same-sex fighting, to seasonal aggression, to maternal aggression is that aggression is made up of both the motivation and decision to aggress, an *appetitive phase,* and the physical, rewarding act of carrying out aggression, a *consummatory phase.* By thinking of aggression in this way we can understand from an adaptive perspective what drives motivation to fight in an adaptive sense, what drives the escalation and termination of fighting, and what happens when these processes go wrong. Practically, coding aggressive behaviors is a slow process that requires considerable observer time and effort that has made these studies time consuming to complete. Understanding these aspects of aggression will give better insight into human maladaptive aggression brought on by factors such as substance use disorders and neuropsychiatric conditions that often involve exaggerated risk seeking behaviors that can lead to inappropriate aggression.

However, studying aggression has always been complex due to the number of contexts it can occur in and the different behaviors it can entail. Aggression is a highly variable behavior across individuals which can make it difficult to create a sample of animals with the correct phenotype to carry out a specific behavioral experiment such as social defeat. Aggression can also be expressed in many ways (i.e., biting, pinning, jabbing) and can be either offensive, attacking another, or defensive, protecting oneself from attack, and as such experiments can be slowed by the process of scoring aggressive behaviors in clinically (and ecologically) relevant paradigms. Taken together, individual variability and a heavy scoring load have made high-throughput aggression research difficult. But now, elegant computational and machine learning systems are being introduced to speed up both of these processes. Animals can now be computational prescreened over a series of days for their behavioral phenotypes using tools such as through the structural equation modeling approach Mouse Aggression Detector (Kwiatkowski et al., 2021) in order to find suitable animals for specific behavioral tests of aggression. Behavior can also be quickly and easily quantified using machine learning pose estimation tools such as DeepLabCut (Mathis et al., 2018) and SimBA (Nilsson et al., 2020). These tools are revolutionizing the study of behavior and allows researchers to use elegant behavioral designs with quick quantification.

One highlight of this review is that while aggression happens in a variety of contexts, many of the brain regions and neuroendocrine mechanisms that underlie aggression are conserved across types. For example, much of our knowledge of the brain regions and circuits tied to aggression across contexts in rodents involve the olfactory system first and then control by aspects of the social decision making network. These brain regions are then activated or inhibited by neuroendocrine mechanisms important to sociality and reward including OXT, AVP, serotonin, DA and others as reviewed above. However, it is possible that other brain regions outside of the social decision making network may also play a major role in aggression and have simply been to this point unstudied. With the advent of whole brain light sheet microscopy (Keller & Ahrens, 2015), a way to visualize brain activation and connectivity across the whole brain in three dimensions, we are at an exciting time where new brain regions or new connections between brain regions may be found to be active in aggressive behavior. This process will make seeking out new regions of interest easier than ever before, and with machine learning for behavioral scoring and the genetic and viral tools now available such as DREADDs or optogenetics that can target specific cell types and brain regions for manipulation.

Aggression research provides a wide insight into the brain extending from the basic ecology of animals and how they decide to fight and maintain the resources they need to survive to applied clinical applications for neuropsychiatric and substance use disorders. As such, continuing aggression research forward will be of great value to the scientific community at large as well as to public health. The advent of new technologies has aggression researchers on the edge of a high throughput revolution that will quickly advance our knowledge of not only aggression but also motivation, risk seeking and decision making in exciting ways.

References

Abbasi, S., Raza, S., Azam, S. S., Liedl, K. R., & Fuchs, J. E. (2016). Interaction mechanisms of a melatonergic inhibitor in the melatonin synthesis pathway. *Journal of Molecular Liquids*, *221*, 507–517. https://doi.org/10.1016/j.molliq.2016.06.034

Albers, H. E. (2012). The regulation of social recognition, social communication and aggression: Vasopressin in the social behavior neural network. *Hormones and Behavior*, *61*(3), 283–292. https://doi.org/10.1016/j.yhbeh.2011.10.007

Albers, H. E., & Bamshad, M. (1998). Role of vasopressin and oxytocin in the control of social behavior in Syrian hamsters (Mesocricetus auratus). *Progress in Brain Research*, *119*(C), 395–408. https://doi.org/10.1016/S0079-6123(08)61583-6

Albers, H. E., Dean, A., Karom, M. C., Smith, D., & Huhman, K. L. (2006). Role of V1a vasopressin receptors in the control of aggression in Syrian hamsters. *Brain Research*, 1073-1074, 425–430. https://doi.org/10.1016/j.brainres.2005.12.081

Aleyasin, H., Flanigan, M. E., Golden, S. A., Takahashi, A., Menard, C., Pfau, M. L., Multer, J., Pina, J., McCabe, K. A., Bhatti, N., Hodes, G. E., Heshmati, M., Neve, R. L., Nestler, E. J., Heller, E. A., & Russo, S. J. (2018). Cell-type-specific role of Δfosb in nucleus accumbens in modulating intermale aggression. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *38*(26), 5913–5924. https://doi.org/10.1523/JNEUROSCI.0296-18.2018

Arakawa, H. (2021). Dynamic regulation of oxytocin neuronal circuits in the sequential processes of prosocial behavior in rodent models. *Current Research in Neurobiology*, *2*, 100011. https://doi.org/10.1016/j.crneur.2021.100011

Attili, G., & Hinde, R. A. (1986). Categories of aggression and their motivational heterogeneity. *Ethology and Sociobiology*, *7*(1), 17–27. https://doi.org/10.1016/0162-3095(86)90012-9

Auger, C. J., Coss, D., Auger, A. P., & Forbes-Lorman, R. M. (2011). Epigenetic control of vasopressin expression is maintained by steroid hormones in the adult male rat brain. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(10), 4242–4247. https://doi.org/10.1073/pnas.1100314108

Banerjee, A., Phelps, S. M., & Long, M. A. (2019). Singing mice. *Current Biology*, *29*(6), R190–R191. https://doi.org/10.1016/j.cub.2018.11.048

Bayerl, D. S., Klampfl, S. M., & Bosch, O. J. (2019). More than reproduction: Central gonadotropin-releasing hormone antagonism decreases maternal aggression in lactating rats. *Journal of Neuroendocrinology*, *31*(9), e12709. https://doi.org/10.1111/jne.12709

Beach, S. R. H., Brody, G. H., Gunter, T. D., Packer, H., Wernett, P., & Philibert, R. A. (2010). Child maltreatment moderates the association of MAOA with symptoms of depression and antisocial personality disorder. *Journal of Family Psychology*, *24*(1), 12–20. https://doi.org/10.1037/a0018074

Beck, S. G., & Handa, R. J. (2004). Dehydroepiandrosterone (DHEA): A misunderstood adrenal hormone and spine-tingling neurosteroid? *Endocrinology*, *145*(3), 1039–1041. https://doi.org/10.1210/en.2003-1703

Becker, E. A., Leithead, A. B., Libo, N., Kumerow, M. T., Goetsch, L., & Marler, C. A. (2021). Transmission of paternal retrieval behavior from fathers to sons in a biparental rodent. *Developmental Psychobiology*, *63*(6), e22164. https://doi.org/10.1002/dev.22164

Becker, E. A., Moore, B. M., Auger, C., & Marler, C. A. (2010). Paternal behavior increases testosterone levels in offspring of the California mouse. *Hormones and Behavior*, *58*(3), 385–389. https://doi.org/10.1016/j.yhbeh.2010.03.019

Been, L. E., Gibbons, A. B., & Meisel, R. L. (2019). Towards a neurobiology of female aggression. *Neuropharmacology*, *156*, 107451. https://doi.org/10.1016/j.neuropharm.2018.11.039

Beery, A. K., & Zucker, I. (2010). Oxytocin and same-sex social behavior in female meadow voles. *Neuroscience*, *169*(2), 665–673. https://doi.org/10.1016/j.neuroscience.2010.05.023

Beery, A. K., Vahaba, D. M., & Grunberg, D. M. (2014). Corticotropin-releasing factor receptor densities vary with photoperiod and sociality. *Hormones and Behavior*, *66*(5), 779–786. https://doi.org/10.1016/j.yhbeh.2014.08.014

Beiderbeck, D. I., Neumann, I. D., & Veenema, A. H. (2007). Differences in intermale aggression are accompanied by opposite vasopressin release patterns within the septum in rats bred for low and high anxiety. *The European Journal of Neuroscience*, *26*(12), 3597–3605. https://doi.org/10.1111/j.1460-9568.2007.05974.x

Bell, M. R. (2018). Comparing postnatal development of gonadal hormones and associated social behaviors in rats, mice, and humans. *Endocrinology*, *159*(7), 2596–2613. https://doi.org/10.1210/en.2018-00220

Benarroch, E. E. (2008). Suprachiasmatic nucleus and melatonin: Reciprocal interactions and clinical correlations. *Neurology*, *71*(8), 594–598. https://doi.org/10.1212/01.wnl.0000324283.57261.37

Bentz, A. B., Dossey, E. K., & Rosvall, K. A. (2019). Tissue-specific gene regulation corresponds with seasonal plasticity in female testosterone. *General and Comparative Endocrinology*, *270*, 26–34. https://doi.org/10.1016/j.ygcen.2018.10.001

Bester-Meredith, J. K., Young, L. J., & Marler, C. A. (1999). Species differences in paternal behavior and aggression in peromyscus and their associations with vasopressin immunoreactivity and receptors. *Hormones and Behavior*, *36*(1), 25–38. https://doi.org/10.1006/hbeh.1999.1522

Bielsky, I. F., & Young, L. J. (2004). Oxytocin, vasopressin, and social recognition in mammals. *Peptides*, *25*(9), 1565–1574. https://doi.org/10.1016/j.peptides.2004.05.019

Birkett, M., & Fite, K. V. (2005). Diurnal variation in serotonin immunoreactivity in the dorsal raphe nucleus. *Brain Research*, *1034*(1–2), 180–184. https://doi.org/10.1016/j.brainres.2004.11.053

Blanchard, R. J., Hori, K., Tom, P., & Blanchard, D. C. (1988). Social-dominance and individual aggressiveness. *Aggressive Behavior*, *14*(3), 195–203. https://doi.org/10.1002/1098-2337(1988)14:3<195::AID-AB2480140305>3.0.CO;2-G

Borland, J. M., Walton, J. C., Norvelle, A., Grantham, K. N., Aiani, L. M., Larkin, T. E., McCann, K. E., & Albers, H. E. (2020). Social experience and sex-dependent regulation of aggression in the lateral septum by extrasynaptic delta GABA(A) receptors. *Psychopharmacology*, *237*(2), 329–344. https://doi.org/10.1007/s00213-019-

Bosch, O. J. (2013). Maternal aggression in rodents: Brain oxytocin and vasopressin mediate pup defence. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*(1631), 20130085. https://doi.org/10.1098/rstb.2013.0085

Bosch, O. J., & Neumann, I. D. (2010). Vasopressin released within the central amygdala promotes maternal aggression. *The European Journal of Neuroscience*, *31*(5), 883–891. https://doi.org/10.1111/j.1460-9568.2010.07115.x

Bosch, O. J., & Neumann, I. D. (2012). Both oxytocin and vasopressin are mediators of maternal care and aggression in rodents: From central release to sites of action. *Hormones and Behavior*, *61*, 293–303.

Bosch, O. J., Meddle, S. L., Beiderbeck, D. I., Douglas, A. J., & Neumann, I. D. (2005). Brain oxytocin correlates with maternal aggression: Link to anxiety. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *25*(29), 6807–6815. https://doi.org/10.1523/JNEUROSCI.1342-05.2005

Bosch, O. J., Pförtsch, J., Beiderbeck, D. I., Landgraf, R., & Neumann, I. D. (2010). Maternal behaviour is associated with vasopressin release in the medial preoptic area and bed nucleus of the stria terminalis in the rat. *Journal of Neuroendocrinology*, *22*(5), 420–429. https://doi.org/10.1111/j.1365-2826.2010.01984.x

Breedveld, M. C., Folkertsma, R., & Eccard, J. A. (2019). Rodent mothers increase vigilance behaviour when facing infanticide risk. *Scientific Reports*, *9*(1), 12054. https://doi.org/10.1038/s41598-019-48459-9

Bridges, R. S. (2015). Neuroendocrine regulation of maternal behavior. *Frontiers in Neuroendocrinology*, *36*, 178–196. https://doi.org/10.1016/j.yfrne.2014.11.007

Burnett, C. J., Funderburk, S. C., Navarrete, J., Sabol, A., Liang-Guallpa, J., Desrochers, T. M., & Krashes, M. J. (2019). Need-based prioritization of behavior. *eLife*, *8*, e44527. https://doi.org/10.7554/eLife.44527

Calcagnoli, F., de Boer, S. F., Althaus, M., den Boer, J. A., & Koolhaas, J. M. (2013). Antiaggressive activity of central oxytocin in male rats. *Psychopharmacology*, *229*(4), 639–651. https://doi.org/10.1007/s00213-013-3124-7

Calcagnoli, F., de Boer, S. F., Beiderbeck, D. I., Althaus, M., Koolhaas, J. M., & Neumann, I. D. (2014). Local oxytocin expression and oxytocin receptor binding in the male rat brain is associated with aggressiveness. *Behavioural Brain Research*, *261*, 315–322. https://doi.org/10.1016/j.bbr.2013.12.050

Calcagnoli, F., Stubbendorff, C., Meyer, N., de Boer, S. F., Althaus, M., & Koolhaas, J. M. (2015). Oxytocin microinjected into the central amygdaloid nuclei exerts anti-aggressive effects in male rats. *Neuropharmacology*, *90*, 74–81. https://doi.org/10.1016/j.neuropharm.2014.11.012

Caldwell, G. S., Glickman, S. E., & Smith, E. R. (1984). Seasonal aggression independent of seasonal testosterone in wood rats (hormones/seasonality/agonistic behavior). *Proceedings of the National Academy of Sciences of the United States of America*, *81*(16), 5255–5257. https://doi.org/10.1073/pnas.81.16.5255

Caldwell, G. S., Glickman, S. E., & Smith, E. R. (1984). Seasonal aggression independent of seasonal testosterone in wood rats. *Proceedings of the National Academy of Sciences of the United States of America*, *81*(16), 5255–5257. https://doi.org/10.1073/pnas.81.16.5255

Caldwell, H. K., & Albers, H. E. (2004). Effect of photoperiod on vasopressin-induced aggression in Syrian hamsters. *Hormones and Behavior*, *46*(4), 444–449. https://doi.org/10.1016/j.yhbeh.2004.04.006

Cameron, J. L. (2004). Interrelationships between hormones, behavior, and affect during adolescence: Understanding hormonal, physical, and brain changes occurring in association with pubertal activation of the reproductive axis. Introduction to part III. *Annals of the New York Academy of Sciences*, *1021*(1), 110–123. https://doi.org/10.1196/annals.1308.012

Carrillo, M., Ricci, L. A., & Melloni, R. H. (2011). Developmental and withdrawal effects of adolescent AAS exposure on the glutamatergic system in hamsters. *Behavioral Neuroscience*, *125*(3), 452–464. https://doi.org/10.1037/a0023475

Carrillo, M., Ricci, L. A., & Melloni, R. H., Jr. (2009). Adolescent anabolic androgenic steroids reorganize the glutamatergic neural circuitry in the hypothalamus. *Brain Research*, *1249*, 118–127. https://doi.org/10.1016/j.brainres.2008.10.053

Checkley, S. A., Murphy, D. G., Abbas, M., Marks, M., Winton, F., Palazidou, E., Murphy, D. M., Franey, C., & Arendt, J. (1993). Melatonin rhythms in seasonal affective disorder. *The British Journal of Psychiatry*, *163*(3), 332–337. https://doi.org/10.1192/bjp.163.3.332

Cheng, S. Y., & Delville, Y. (2010). Play fighting and corticotropin-releasing hormone in the lateral septum of golden hamsters. *Neuroscience*, *169*(1), 236–245. https://doi.org/10.1016/j.neuroscience.2010.04.040

Cheng, S. Y., Taravosh-Lahn, K., & Delville, Y. (2008). Neural circuitry of play fighting in golden hamsters. *Neuroscience*, *156*(2), 247–256. https://doi.org/10.1016/j.neuroscience.2008.07.048

Consiglio, A. R., Borsoi, A., Pereira, G. A. M., & Lucion, A. B. (2005). Effects of oxytocin microinjected into the central amygdaloid nucleus and bed nucleus of stria terminalis on maternal aggressive behavior in rats. *Physiology & Behavior*, *85*(3), 354–362. https://doi.org/10.1016/j.physbeh.2005.05.002

D'Anna, K. L., & Gammie, S. C. (2006). Hypocretin-1 dose-dependently modulates maternal behaviour in mice. *Journal of Neuroendocrinology*, *18*(8), 553–566. https://doi.org/10.1111/j.1365-2826.2006.01448.x

D'Anna, K. L., & Gammie, S. C. (2009). Activation of corticotropin-releasing factor receptor 2 in lateral septum negatively regulates maternal defense. *Behavioral Neuroscience*, *123*(2), 356–368. https://doi.org/10.1037/a0014987

D'Anna, K. L., Stevenson, S. A., & Gammie, S. C. (2005). Urocortin 1 and 3 impair maternal defense behavior in mice. *Behavioral Neuroscience*, *119*(4), 1061–1071. https://doi.org/10.1037/0735-7044.119.4.1061

da Veiga, C. P., Miczek, K. A., Lucion, A. B., & de Almeida, R. M. (2011). Social instigation and aggression in postpartum female rats: Role of 5-Ht1A and 5-Ht1B receptors in the dorsal raphé nucleus and prefrontal cortex. *Psychopharmacology*, *213*(2-3), 475–487. https://doi.org/10.1007/s00213-010-2083-5

Davis, E. S., & Marler, C. A. (2003). The progesterone challenge: Steroid hormone changes following a simulated territorial intrusion in female Peromyscus californicus. *Hormones and Behavior*, *44*(3), 185–198. https://doi.org/10.1016/S0018-506X(03)00128-4

De Almeida, R. M. M., & Lucion, A. B. (1997). 8-OH-DPAT in the median raphe, dorsal periaqueductal gray and corticomedial amygdala nucleus decreases, but in the medial septal area it can increase maternal aggressive behavior in rats. *Psychopharmacology*, *134*(4), 392–400. https://doi.org/10.1007/s002130050476

de Jong, T. R., & Neumann, I. D. (2018). Oxytocin and aggression. *Current Topics in Behavioral Neurosciences*, *35*, 175–192. https://doi.org/10.1007/7854_2017_13

De Vries, G. J., al-Shamma, H. A., & Zhou, L. (1994). The sexually dimorphic vasopressin innervation of the brain as a model for steroid modulation of neuropeptide transmission. *Annals of the New York Academy of Sciences*, *743*(1), 95–120. https://doi.org/10.1111/j.1749-6632.1994.tb55789.x

DeLeon, K. R., Grimes, J. M., Connor, D. F., & Melloni, R. H., Jr. (2002). Adolescent cocaine exposure and offensive aggression: Involvement of serotonin neural signaling and innervation in male Syrian hamsters. *Behavioural Brain Research*, *133*(2), 211–220. https://doi.org/10.1016/S0166-4328(02)00004-9

Delville, Y., Melloni, R. H., Jr., & Ferris, C. F. (1998). Behavioral and neurobiological consequences of social subjugation during puberty in golden hamsters. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *18*(7), 2667–2672. https://doi.org/10.1523/JNEUROSCI.18-07-02667.1998

Demas, G. E., Polacek, K. M., Durazzo, A., & Jasnow, A. M. (2004). Adrenal hormones mediate melatonin-induced increases in aggression in male Siberian hamsters (Phodopus sungorus). *Hormones and Behavior*, *46*(5), 582–591. https://doi.org/10.1016/j.yhbeh.2004.07.001

Douglas, A. J., Meddle, S. L., Kroemer, S., Muesch, W., Bosch, O. J., & Neumann, I. D. (2007). Social stress induces hypothalamo-pituitary-adrenal axis responses in lactating rats bred for high trait anxiety. *The European Journal of Neuroscience*, *25*(5), 1599–1603. https://doi.org/10.1111/j.1460-9568.2007.05380.x

Dumais, K. M., & Veenema, A. H. (2016). Vasopressin and oxytocin receptor systems in the brain: Sex differences and sex-specific regulation of social behavior. *Frontiers in Neuroendocrinology*, *40*, 1–23. https://doi.org/10.1016/j.yfrne.2015.04.003

Duque-Wilckens, N., Trainor, B. C., & Marler, C. A. (2019). Aggression and territoriality. In J. C. Choe (Ed.), *Encyclopedia of animal behavior* (Second Edition, pp. 539–546). https://doi.org/10.1016/B978-0-12-809633-8.90064-5

Duque-Wilckens, N., & Trainor, B. C. (2017). Behavioral neuroendocrinology of female aggression. *Oxford research encyclopedia of neuroscience*. https://doi.org/10.1093/acrefore/9780190264086.013.11

Eaton, G. G., Johnson, D. F., Glick, B. B., & Worlein, J. M. (1986). Japanese macaques (Macaca fuscata) social development: Sex differences in juvenile behavior. *Primates*, *27*(2), 141–150. https://doi.org/10.1007/BF02382594

Edwards, D. A., Nahai, F. R., & Wright, P. (1993). Pathways linking the olfactory bulbs with the medial preoptic anterior hypothalamus are important for intermale aggression in mice. *Physiology & Behavior*, *53*(3), 611–615. https://doi.org/10.1016/0031-9384(93)90162-9

Erskine, M. S., Denenberg, V. H., & Goldman, B. D. (1978). Aggression in the lactating rat: Effects of intruder age and test arena. *Behavioral Biology*, *23*(1), 52–66. https://doi.org/10.1016/S0091-6773(78)91148-3

Everts, H. G. J., De Ruiter, A. J. H., & Koolhaas, J. M. (1997). Differential lateral septal vasopressin in wild-type rats: Correlation with aggression. *Hormones and Behavior*, *31*(2), 136–144. https://doi.org/10.1006/hbeh.1997.1375

Farrell, S. F., & McGinnis, M. Y. (2003). Effects of pubertal anabolic-androgenic steroid (AAS) administration on reproductive and aggressive behaviors in male rats. *Behavioral Neuroscience*, *117*(5), 904–911. https://doi.org/10.1037/0735-7044.117.5.904

Fernandez-Guasti, A., Swaab, D., & Rodríguez-Manzo, G. (2003). Sexual behavior reduces hypothalamic androgen receptor immunoreactivity. *Psychoneuroendocrinology*, *28*(4), 501–512. https://doi.org/10.1016/S0306-4530(02)00036-7

Ferris, C. F. (2000). Adolescent stress and neural plasticity in hamsters: A vasopressin-serotonin model of inappropriate aggressive behaviour. *Experimental Physiology*, *85*(s1), 85S–90S. https://doi.org/10.1111/j.1469-445X.2000.tb00011.x

Ferris, C. F. (2005). Vasopressin/oxytocin and aggression. Novartis Foundation Symposium, 268, 190–198. https://doi.org/10.1002/0470010703.CH13

Ferris, C. F., & Potegal, M. (1988). Vasopressin receptor blockade in the anterior hypothalamus suppresses aggression in hamsters. *Physiology & Behavior*, *44*(2), 235–239. https://doi.org/10.1016/0031-9384(88)90144-8

Ferris, C. F., Foote, K. B., Meltser, H. M., Plenby, M. G., Smith, K. L., & Insel, T. R. (1992). Oxytocin in the amygdala facilitates maternal aggression. *Annals of the New York Academy of Sciences*, *652*(1), 456–457. https://doi.org/10.1111/j.1749-6632.1992.tb34382.x

Ferris, C. F., Jr., Melloni, R. H., Jr., Koppel, G., Perry, K. W., Fuller, R. W., & Delville, Y. (1997). Vasopressin/serotonin interactions in the anterior hypothalamus control aggressive behavior in golden hamsters. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *17*(11), 4331–4340. https://doi.org/10.1523/JNEUROSCI.17-11-04331.1997

Ferris, C. F., Stolberg, T., & Delville, Y. (1999). Serotonin regulation of aggressive behavior in male golden hamsters (Mesocricetus auratus). *Behavioral Neuroscience*, *113*(4), 804–815. https://doi.org/10.1037/0735-7044.113.4.804

Ficks, C. A., & Waldman, I. D. (2014). Candidate genes for aggression and antisocial behavior: A meta-analysis of association studies of the 5HTTLPR and MAOA - uVNTR. *Behavior Genetics*, *44*(5), 427–444. https://doi.org/10.1007/S10519-014-9661-Y

Field, E. F., Whishaw, I. Q., Pellis, S. M., & Watson, N. V. (2006). Play fighting in androgen-insensitive tfm rats: Evidence that androgen receptors are necessary for the development of adult playful attack and defense. *Developmental Psychobiology*, *48*(2), 111–120. https://doi.org/10.1002/dev.20121

Finney, H. C., & Erpino, M. J. (1976). Synergistic effect of estradiol benzoate and dihydrotestosterone on aggression in mice. *Hormones and Behavior*, *7*(4), 391–400. https://doi.org/10.1016/0018-506X(76)90010-6

Fischer, S., Pujol, N. T., Bolton, R., Hurst, J. L., & Stockley, P. (2018). Communal breeding affects offspring behaviours associated with a competitive social environment. *Scientific Reports*, *8*(1), Article 16850. https://doi.org/10.1038/s41598-018-35089-w

Fish, E. W., De Bold, J. F., & Miczek, K. A. (2002). Aggressive behavior as a reinforcer in mice: activation by allopregnanolone. *Psychopharmacology*, *163*(3-4), 459–466. https://doi.org/10.1007/s00213-002-1211-2

Flandreau, E. I., Ressler, K. J., Owens, M. J., & Nemeroff, C. B. (2012). Chronic overexpression of corticotropin-releasing factor from the central amygdala produces HPA axis hyperactivity and behavioral anxiety associated with gene-expression changes in the hippocampus and paraventricular nucleus of the hypothalamus. *Psychoneuroendocrinology*, *37*(1), 27–38. https://doi.org/10.1016/j.psyneuen.2011.04.014

Flanigan, M., Aleyasin, H., Takahashi, A., Golden, S. A., & Russo, S. J. (2017). An emerging role for the lateral habenula in aggressive behavior. In. *Pharmacology Biochemistry and Behavior*, *162*, 79–86. https://doi.org/10.1016/j.pbb.2017.05.003

Floody, O. R. (1983). Hormones and aggression in female mammals. In B. B. Svare (Ed.), *Hormones and aggressive behavior* (pp. 39–89). Springer U.S. https://doi.org/10.1007/978-1-4613-3521-4_3

Frau, R., Fanni, S., Serra, V., Simola, N., Godar, S. C., Traccis, F., Devoto, P., Bortolato, M., & Melis, M. (2019). Dysfunctional mesocortical dopamine circuit at pre-adolescence is associated to aggressive behavior in MAO-A hypomorphic mice exposed to early life stress. *Neuropharmacology*, *159*, 107517. https://doi.org/10.1016/j.neuropharm.2019.01.032

Frazier, C. R. M., Trainor, B. C., Cravens, C. J., Whitney, T. K., & Marler, C. A. (2006). Paternal behavior influences development of aggression and vasopressin expression in male California mouse offspring. *Hormones and Behavior*, *50*(5), 699–707. https://doi.org/10.1016/j.yhbeh.2006.06.035

Fuxjager, M. J., & Marler, C. A. (2010). How and why the winner effect forms: Influences of contest environment and species differences. *Behavioral Ecology*, *21*(1), 37–45. https://doi.org/10.1093/beheco/arp148

Fuxjager, M. J., Foufopoulos, J., Diaz-Uriarte, R., & Marler, C. A. (2011). Functionally opposing effects of testosterone on two different types of parasite: Implications for the immunocompetence handicap hypothesis. *Functional Ecology*, *25*(1), 132–138. https://doi.org/10.1111/j.1365-2435.2010.01784.x

Fuxjager, M. J., Montgomery, J. L., Becker, E. A., & Marler, C. A. (2010). Deciding to win: Interactive effects of residency, resources and 'boldness' on contest outcome in white-footed mice. *Animal Behaviour*, *80*(5), 921–927. https://doi.org/10.1016/j.anbehav.2010.08.018

Fuxjager, M. J., Zhao, X., Rieger, N. S., & Marler, C. A. (2018). Why animals fight: uncovering the function and mechanisms of territorial aggression. In J. Call, G. M. Burghardt, I. M. Pepperberg, C. T. Snowdon, & T. Zentall (Eds.), *APA handbook of comparative psychology: Basic concepts, methods, neural substrate, and behavior* (pp. 853–875). American Psychological Association. https://doi.org/10.1037/0000011-041

Gammie, S. C., D'Anna, K. L., Gerstein, H., & Stevenson, S. A. (2009). Neurotensin inversely modulates maternal aggression. *Neuroscience*, *158*(4), 1215–1223. https://doi.org/10.1016/j.neuroscience.2008.11.045

Gammie, S. C., Negron, A., Newman, S. M., & Rhodes, J. S. (2004). Corticotropin-releasing factor inhibits maternal aggression in mice. *Behavioral Neuroscience*, *118*(4), 805–814. https://doi.org/10.1037/0735-7044.118.4.805

Gammie, S. C., Seasholtz, A. F., & Stevenson, S. A. (2008). Deletion of corticotropin-releasing factor binding protein selectively impairs maternal, but not intermale aggression. *Neuroscience*, *157*(3), 502–512. https://doi.org/10.1016/j.neuroscience.2008.09.026

Gammie, S. C., & Nelson, R. J. (2001). cFOS and pCREB activation and maternal aggression in mice. *Brain Research*, *898*(2), 232–241. https://doi.org/10.1016/S0006-8993(01)02189-8

Gee, D. G., Bath, K. G., Johnson, C. M., Meyer, H. C., Murty, V. P., van den Bos, W., & Hartley, C. A. (2018). Neurocognitive development of motivated behavior: Dynamic changes across childhood and adolescence. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *38*(44), 9433–9445. https://doi.org/10.1523/JNEUROSCI.1674-18.2018

Gleason, E. D., Fuxjager, M. J., Oyegbile, T. O., & Marler, C. A. (2009). Testosterone release and social context: When it occurs and why. *Frontiers in Neuroendocrinology*, *30*(4), 460–469. https://doi.org/10.1016/j.yfrne.2009.04.009

Golden, S. A., & Shaham, Y. (2018). Aggression addiction and relapse: A new frontier in psychiatry. *Neuropsychopharmacology*, *43*(1), 224–225. https://doi.org/10.1038/npp.2017.173

Golden, S. A., Heshmati, M., Flanigan, M., Christoffel, D. J., Guise, K., Pfau, M. L., Aleyasin, H., Menard, C., Zhang, H., Hodes, G. E., Bregman, D., Khibnik, L., Tai, J., Rebusi, N., Krawitz, B., Chaudhury, D., Walsh, J. J., Han, M.-H., Shapiro, M. L., & Russo, S. J. (2016). Basal forebrain projections to the lateral habenula modulate aggression reward. *Nature*, *534*(7609), 688–692. https://doi.org/10.1038/nature18601

Golden, S. A., Jin, M., Heins, C., Venniro, M., Michaelides, M., & Shaham, Y. (2019). Nucleus accumbens Drd1-expressing neurons control aggression self-administration and aggression seeking in mice. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *39*(13), 2482–2496. https://doi.org/10.1523/JNEUROSCI.2409-18.2019

Golden, S. A., Jin, M., & Shaham, Y. (2019). Animal models of (or for) aggression reward, addiction, and relapse: Behavior and circuits. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *39*(21), 3996–4008. https://doi.org/10.1523/JNEUROSCI.0151-19.2019

Goymann, W., Moore, I. T., & Oliveira, R. F. (2019). Challenge hypothesis 2.0: A fresh look at an established idea. *Bioscience*, *69*, 432–442. https://doi.org/10.1093/biosci/biz041

Goymann, W., Wittenzellner, A., Schwabl, I., Makomba, M., Albert, D. J., Jonik, R. H., . . . Crews, D. (2008). Progesterone modulates aggression in sex-role reversed female African black coucals. *Proceedings. Biological Sciences*, *275*(1638), 1053–1060. https://doi.org/10.1098/rspb.2007.1707

Greenberg, G. D., Steinman, M. Q., Doig, I. E., Hao, R., & Trainor, B. C. (2015). Effects of social defeat on dopamine neurons in the ventral tegmental area in male and female California mice. *The European Journal of Neuroscience*, *42*(12), 3081–3094. https://doi.org/10.1111/ejn.13099

Grieb, Z. A., & Lonstein, J. S. (2021). Oxytocin receptor expression in the midbrain dorsal raphe is dynamic across female reproduction in rats. *Journal of Neuroendocrinology*, *33*(2), e12926. https://doi.org/10.1111/jne.12926

Griffin, A. (2017). Adolescent neurological development and implications for health and well-being. *Healthcare*, *5*(4), 62–69. https://doi.org/10.3390/healthcare5040062

Grimes, J. M., & Melloni, R. H., Jr. (2002). Serotonin modulates offensive attack in adolescent anabolic steroid-treated hamsters. *Pharmacology, Biochemistry, and Behavior*, *73*(3), 713–721. https://doi.org/10.1016/S0091-3057(02)00880-8

Grimes, J. M., Ricci, L. A., & Melloni, R. H., Jr. (2003). Glutamic acid decarboxylase (GAD65) immunoreactivity in brains of aggressive, adolescent anabolic steroid-treated hamsters. *Hormones and Behavior*, *44*(3), 271–280. https://doi.org/10.1016/S0018-506X(03)00138-7

Grotzinger, A. D., Mann, F. D., Patterson, M. W., Herzhoff, K., Tackett, J. L., Tucker-Drob, E. M., & Paige Harden, K. (2018). Twin models of environmental and genetic influences on pubertal development, salivary testosterone, and estradiol in adolescence. *Horumon to Rinsho*, *88*(2), 243–250. https://doi.org/10.1111/cen.13522

Guerra, R. F., Takase, E., & de O Nunes, C. R. (1999). Play fighting of juvenile golden hamsters (Mesocricetus auratus): Effects of two types of social deprivation and days of testing. *Behavioural Processes*, *47*(3), 139–151. https://doi.org/10.1016/S0376-6357(99)00058-3

Harmon, A. C., Huhman, K. L., Moore, T. O., & Albers, H. E. (2002). Oxytocin inhibits aggression in female Syrian hamsters. *Journal of Neuroendocrinology*, *14*(12), 963–969. https://doi.org/10.1046/j.1365-2826.2002.00863.x

Hasen, N. S., & Gammie, S. C. (2006). Maternal aggression: New insights from Egr-1. *Brain Research*, *1108*(1), 147–156. https://doi.org/10.1016/j.brainres.2006.06.007

Hashikawa, K., Hashikawa, Y., Falkner, A., & Lin, D. (2016). The neural circuits of mating and fighting in male mice. *Current Opinion in Neurobiology*, *38*, 27–37. https://doi.org/10.1016/j.conb.2016.01.006

Hashikawa, K., Hashikawa, Y., Lischinsky, J., & Lin, D. (2018). The neural mechanisms of sexually dimorphic aggressive behaviors. *Trends in Genetics*, *34*(10), 755–776. https://doi.org/10.1016/j.tig.2018.07.001

Hathaway, G. A., Faykoo-Martinez, M., Peragine, D. E., Mooney, S. J., & Holmes, M. M. (2016). Subcaste differences in neural activation suggest a prosocial role for oxytocin in eusocial naked mole-rats. *Hormones and Behavior*, *79*, 1–7. https://doi.org/10.1016/j.yhbeh.2015.12.001

Herman, J. P., Mueller, N. K., & Figueiredo, H. (2004). Role of GABA and glutamate circuitry in hypothalamo-pituitary-adrenocortical stress integration. *Annals of the New York Academy of Sciences*, *1018*(1), 35–45. https://doi.org/10.1196/annals.1296.004

Herting, M. M., Gautam, P., Spielberg, J. M., Kan, E., Dahl, R. E., & Sowell, E. R. (2014). The role of testosterone and estradiol in brain volume changes across adolescence: A longitudinal structural MRI study. *Human Brain Mapping*, *35*(11), 5633–5645. https://doi.org/10.1002/hbm.22575

Holloway, K. S., & Suter, R. B. (2004). Play deprivation without social isolation: Housing controls. *Developmental Psychobiology*, *44*(1), 58–67. https://doi.org/10.1002/dev.10151

Holschbach, M. A., Vitale, E. M., & Lonstein, J. S. (2018). Serotonin-specific lesions of the dorsal raphe disrupt maternal aggression and caregiving in postpartum rats. *Behavioural Brain Research*, *348*, 53–64. https://doi.org/10.1016/j.bbr.2018.04.008

Homberg, J. R., Schiepers, O. J. G., Schoffelmeer, A. N. M., Cuppen, E., & Vanderschuren, L. J. M. J. (2007). Acute and constitutive increases in central serotonin levels reduce social play behaviour in peri-adolescent rats. *Psychopharmacology*, *195*(2), 175–182. https://doi.org/10.1007/s00213-007-0895-8

Hsu, Y., Earley, R. L., & Wolf, L. L. (2006). Modulation of aggressive behaviour by fighting experience: Mechanisms and contest outcomes. *Biological Reviews of the Cambridge Philosophical Society*, *81*(1), 33–74. https://doi.org/10.1017/S146479310500686X

Hu, R. K., Zuo, Y., Ly, T., Wang, J., Meera, P., Wu, Y. E., & Hong, W. (2021). An amygdala-to-hypothalamus circuit for social reward. *Nature Neuroscience*, *24*(6), 831–842. https://doi.org/10.1038/s41593-021-00828-2

Hung, L. W., Neuner, S., Polepalli, J. S., Beier, K. T., Wright, M., Walsh, J. J., Lewis, E. M., Luo, L., Deisseroth, K., Dölen, G., & Malenka, R. C. (2017). Gating of social reward by oxytocin in the ventral tegmental area. *Science*, *357*(6358), 1406–1411. https://doi.org/10.1126/science.aan4994

Husak, J. F., Fuxjager, M. J., Johnson, M. A., Vitousek, M. N., Donald, J. W., Francis, C. D., Goymann, W., Hau, M., Kircher, B. K., Knapp, R., Martin, L. B., Miller, E. T., Schoenle, L. A., & Williams, T. D. (2021). Life history and environment predict variation in testosterone across vertebrates. *Evolution*, *75*(5), 1003–1010. https://doi.org/10.1111/evo.14216

Ikemoto, S., & Panksepp, J. (1992). The effects of early social isolation on the motivation for social play in juvenile rats. *Developmental Psychobiology*, *25*(4), 261–274. https://doi.org/10.1002/dev.420250404

Insel, T. R., & Shapiro, L. E. (1992). Oxytocin receptor distribution reflects social organization in monogamous and polygamous voles. *Proceedings of the National Academy of Sciences of the United States of America*, *89*(13), 5981–5985. https://doi.org/10.1073/pnas.89.13.5981

Jasnow, A. M., Huhman, K. L., Bartness, T. J., & Demas, G. E. (2002). Short days and exogenous melatonin increase aggression of male Syrian hamsters (Mesocricetus auratus). *Hormones and Behavior*, *42*(1), 13–20. https://doi.org/10.1006/hbeh.2002.1797

Jennings, J. H., Ung, R. L., Resendez, S. L., Stamatakis, A. M., Taylor, J. G., Huang, J., Veleta, K., Kantak, P. A., Aita, M., Shilling-Scrivo, K., Ramakrishnan, C., Deisseroth, K., Otte, S., & Stuber, G. D. (2015). Visualizing hypothalamic network dynamics for appetitive and consummatory behaviors. *Cell*, *160*(3), 516–527. https://doi.org/10.1016/j.cell.2014.12.026

Juntti, S. A., Tollkuhn, J., Wu, M. V., Fraser, E. J., Soderborg, T., Tan, S., Honda, S.-I., Harada, N., & Shah, N. M. (2010). The androgen receptor governs the execution, but not programming, of male sexual and territorial behaviors. *Neuron*, *66*(2), 260–272. https://doi.org/10.1016/j.neuron.2010.03.024

Juszczak, M., Debeljuk, L., Bartke, A., & Stempniak, B. (1995). Melatonin inhibits oxytocin and vasopressin release from the neurointermediate lobe of the hamster pituitary. *Neuroreport*, *6*(18), 2453–2456. https://doi.org/10.1097/00001756-199512150-00004

Juszczak, M., Wolak, M., Bojanowska, E., Piera, L., & Roszczyk, M. (2016). The role of melatonin membrane receptors in melatonin-dependent oxytocin secretion from the rat hypothalamo-neurohypophysial system - an in vitro and in vivo approach. *Endokrynologia Polska*, *67*(5), 507–514. https://doi.org/10.5603/EP.a2016.0035

Keller, P. J., & Ahrens, M. B. (2015). Visualizing whole-brain activity and development at the single-cell level using light-sheet microscopy. *Neuron*, *85*(3), 462–483. https://doi.org/10.1016/j.neuron.2014.12.039

Klampfl, S. M., Schramm, M. M., Gaßner, B. M., Hübner, K., Seasholtz, A. F., Brunton, P. J., Bayerl, D. S., & Bosch, O. J. (2018). Maternal stress and the MPOA: Activation of CRF receptor 1 impairs maternal behavior and triggers local oxytocin release in lactating rats. *Neuropharmacology*, *133*, 440–450. https://doi.org/10.1016/j.neuropharm.2018.02.019

Klampfl, S. M., Schramm, M. M., Stinnett, G. S., Bayerl, D. S., Seasholtz, A. F., & Bosch, O. J. (2016). Brain CRF-binding protein modulates aspects of maternal behavior under stressful conditions and supports a hypo-anxious state in lactating rats. *Hormones and Behavior*, *84*(2), 136–144. https://doi.org/10.1016/j.yhbeh.2016.06.009

Knyshevski, I., Ricci, L. A., McCann, T. E., & Melloni, R. H., Jr. (2005). Serotonin type-1A receptors modulate adolescent, cocaine-induced offensive aggression in hamsters. *Physiology & Behavior*, *85*(2), 167–176. https://doi.org/10.1016/j.physbeh.2005.03.020

Koolhaas, J. M., Van den Brink, T. H. C., Roozendaal, B., & Boorsma, F. (1990). Medial amygdala and aggressive behavior: Interaction between testosterone and vasopressin. *Aggressive Behavior*, *16*(3–4), 223–229. https://doi.org/10.1002/1098-2337(1990)16:3/4<223::AID-AB2480160308>3.0.CO;2-#

Kozhemyakina, R. V., Shikhevich, S. G., Konoshenko, M. Y., & Gulevich, R. G. (2020). Adolescent oxytocin treatment affects resident behavior in aggressive but not tame adult rats. *Physiology & Behavior*, *224*, 113046. https://doi.org/10.1016/j.physbeh.2020.113046

Kulik, L., Amici, F., Langos, D., & Widdig, A. (2015). Sex differences in the development of aggressive behavior in rhesus macaques (Macaca mulatta). *International Journal of Primatology*, *36*(4), 764–789. https://doi.org/10.1007/s10764-015-9853-1

Kwiatkowski, C. C., Akaeze, H., Ndlebe, I., Goodwin, N., Eagle, A. L., Moon, K., Bender, A. R., Golden, S. A., & Robison, A. J. (2021). Quantitative standardization of resident mouse behavior for studies of aggression and social defeat. *Neuropsychopharmacology*, *46*(9), 1584–1593. https://doi.org/10.1038/s41386-021-01018-1

Kyle, S. C., Burghardt, G. M., & Cooper, M. A. (2019). Development of social play in hamsters: Sex differences and their possible functions. *Brain Research*, *1712*, 217–223. https://doi.org/10.1016/j.brainres.2019.02.012

Lambert, K. G., & Byrnes, E. M. (2019). Challenges to the parental brain: Neuroethological and translational considerations. *Frontiers in Neuroendocrinology*, *53*, 100747. https://doi.org/10.1016/j.yfrne.2019.04.004

Laredo, S. A., Orr, V. N., McMackin, M. Z., & Trainor, B. C. (2014). The effects of exogenous melatonin and melatonin receptor blockade on aggression and estrogen-dependent gene expression in male California mice (Peromyscus californicus). *Physiology & Behavior*, *128*, 86–91. https://doi.org/10.1016/j.physbeh.2014.01.039

Lauritsen, J. L., Fellow, V., & White, N. (2014). BJS special report seasonal patterns in criminal victimization trends. http://www.bjs.gov/content/fellows.cfm

Le Roy, I., Carlier, M., & Roubertoux, P. L. (2001). Sensory and motor development in mice: Genes, environment and their interactions. *Behavioural Brain Research*, *125*(1–2), 57–64. https://doi.org/10.1016/S0166-4328(01)00279-0

Lee, N. S., Goodwin, N. L., Freitas, K. E., & Beery, A. K. (2019). Affiliation, aggression, and selectivity of peer relationships in meadow and prairie voles. *Frontiers in Behavioral Neuroscience*, *13*, 52. https://doi.org/10.3389/fnbeh.2019.00052

Lewis, A. S., Pittenger, S. T., Mineur, Y. S., Stout, D., Smith, P. H., & Picciotto, M. R. (2018). Bidirectional regulation of aggression in mice by hippocampal alpha-7 nicotinic acetylcholine receptors. *Neuropsychopharmacology*, *43*(6), 1267–1275. 2018 43:6, https://doi.org/10.1038/npp.2017.276

Lipshutz, S. E., George, E. M., Bentz, A. B., & Rosvall, K. A. (2019). Evaluating testosterone as a phenotypic integrator: From tissues to individuals to species. *Molecular and Cellular Endocrinology*, *496*, 110531. https://doi.org/10.1016/j.mce.2019.110531

Lischinsky, J. E., & Lin, D. (2020). Neural mechanisms of aggression across species. *Nature Neuroscience*, *23*(11), 1317–1328. https://doi.org/10.1038/s41593-020-00715-2

Liu, Y., Sun, Y., Zhao, X., Kim, J. Y., Luo, L., Wang, Q., Meng, X., Li, Y., Sui, N., Chen, Z.-F., Pan, C., Li, L., & Zhang, Y. (2019). Enhancement of aggression induced by isolation rearing is associated with a lack of central serotonin. *Neuroscience Bulletin*, *35*(5), 841–852. https://doi.org/10.1007/s12264-019-00373-w

Lonstein, J. S. (2019). The dynamic serotonin system of the maternal brain. *Archives of Women's Mental Health*, *22*(2), 237–243. https://doi.org/10.1007/s00737-018-0887-1

Lonstein, J. S., & Gammie, S. C. (2002). Sensory, hormonal, and neural control of maternal aggression in laboratory rodents. *Neuroscience and Biobehavioral Reviews*, *26*(8), 869–888. https://doi.org/10.1016/S0149-7634(02)00087-8

Lu, S. F., McKenna, S. E., Cologer-Clifford, A., Nau, E. A., & Simon, N. G. (1998). Androgen receptor in mouse brain: Sex differences and similarities in autoregulation. *Endocrinology*, *139*(4), 1594–1601. https://doi.org/10.1210/endo.139.4.5863

Lukas, M., Bredewold, R., Neumann, I. D., & Veenema, A. H. (2010). Maternal separation interferes with developmental changes in brain vasopressin and oxytocin receptor binding in male rats. *Neuropharmacology*, *58*(1), 78–87. https://doi.org/10.1016/j.neuropharm.2009.06.020

Lukas, M., Toth, I., Reber, S. O., Slattery, D. A., Veenema, A. H., & Neumann, I. D. (2011). The Neuropeptide oxytocin facilitates pro-social behavior and prevents social avoidance in rats and mice. *Neuropsychopharmacology*, *36*(11), 2159–2168. https://doi.org/10.1038/npp.2011.95

Marler, C. A., & Trainor, B. C. (2020). The challenge hypothesis revisited: Focus on reproductive experience and neural mechanisms. *Hormones and Behavior*, *123*, 104645. https://doi.org/10.1016/j.yhbeh.2019.104645

Marler, C. A., Bester-Meredith, J. K., & Trainor, B. C. (2003). Paternal behavior and aggression: Endocrine mechanisms and nongenomic transmission of behavior. *Advances in the Study of Behavior*, *32*, 263–323. https://doi.org/10.1016/S0065-3454(03)01006-4

Matheson, G. J., Schain, M., Almeida, R., Lundberg, J., Cselényi, Z., Borg, J., Varrone, A., Farde, L., & Cervenka, S. (2015). Diurnal and seasonal variation of the brain serotonin system in healthy male subjects. *NeuroImage*, *112*, 225–231. https://doi.org/10.1016/j.neuroimage.2015.03.007

Mathis, A., Mamidanna, P., Cury, K. M., Abe, T., Murthy, V. N., Mathis, M. W., & Bethge, M. (2018). DeepLabCut: Markerless pose estimation of user-defined body parts with deep learning. *Nature Neuroscience*, *21*(9), 1281–1289. https://doi.org/10.1038/s41593-018-0209-y

McDermott, R., Tingley, D., Cowden, J., Frazzetto, G., & Johnson, D. D. P. (2009). Monoamine oxidase A gene (MAOA) predicts behavioral aggression following provocation. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(7), 2118–2123. https://doi.org/10.1073/pnas.0808376106

McDonald, M. M., Markham, C. M., Norvelle, A., Albers, H. E., & Huhman, K. L. (2012). GABAA receptor activation in the lateral septum reduces the expression of conditioned defeat and increases aggression in Syrian hamsters. *Brain Research*, *1439*, 27–33. https://doi.org/10.1016/j.brainres.2011.12.042

Michels, A. M. (1998). Sex differences in food acquisition and aggression in captive common marmosets (Callithrix jacchus). *Primates*, *39*(4), 549–556. https://doi.org/10.1007/BF02557576

Miczek, K. A., Fish, E. W., De Bold, J. F., & De Almeida, R. M. M. (2002). Social and neural determinants of aggressive behavior: Pharmacotherapeutic targets at serotonin, dopamine and gamma-aminobutyric acid systems. *Psychopharmacology*, *163*(3-4), 434–458. https://doi.org/10.1007/s00213-002-1139-6

Moore, I. T., Hernandez, J., & Goymann, W. (2020). Who rises to the challenge? Testing the Challenge Hypothesis in fish, amphibians, reptiles, and mammals. *Hormones and Behavior*, *123*, 104537. https://doi.org/10.1016/j.yhbeh.2019.06.001

Morrison, T. R., Ricci, L. A., & Melloni, R. H., Jr. (2014). GABA neural signaling in the latero-anterior hypothalamus modulates aggressive behavior in adolescent anabolic/androgenic steroid-treated hamsters. *Behavioural Pharmacology*, *25*(7), 673–683. https://doi.org/10.1097/FBP.0000000000000083

Munley, K. M., Deyoe, J. E., Ren, C. C., & Demas, G. E. (2020). Melatonin mediates seasonal transitions in aggressive behavior and circulating androgen profiles in male Siberian hamsters. *Hormones and Behavior*, *117*, 104608. https://doi.org/10.1016/j.yhbeh.2019.104608

Munley, K. M., Rendon, N. M., & Demas, G. E. (2018). Neural androgen synthesis and aggression: Insights from a seasonally breeding rodent. *Frontiers in Endocrinology*, *9*(APR), 136. https://doi.org/10.3389/fendo.2018.00136

Munley, K. M., Trinidad, J. C., Deyoe, J. E., Adaniya, C. H., Nowakowski, A. M., Ren, C. C., Murphy, G. V., Reinhart, J. M., & Demas, G. E. (2021). Melatonin-dependent changes in neurosteroids are associated with increased aggression in a seasonally breeding rodent. *Journal of Neuroendocrinology*, *33*(3), e12940. https://doi.org/10.1111/jne.12940

Murgatroyd, C., Wigger, A., Frank, E., Singewald, N., Bunck, M., Holsboer, F., Landgraf, R., & Spengler, D. (2004). Impaired repression at a vasopressin promoter polymorphism underlies overexpression of vasopressin in a rat model of trait anxiety. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *24*(35), 7762–7770. https://doi.org/10.1523/JNEUROSCI.1614-04.2004

Nakao, N., Ono, H., Yamamura, T., Anraku, T., Takagi, T., Higashi, K., Yasuo, S., Katou, Y., Kageyama, S., Uno, Y., Kasukawa, T., Iigo, M., Sharp, P. J., Iwasawa, A., Suzuki, Y., Sugano, S., Niimi, T., Mizutani, M., Namikawa, T., . . . Yoshimura, T. (2008). Thyrotrophin in the pars tuberalis triggers photoperiodic response. *Nature*, *452*(7185), 317–322. https://doi.org/10.1038/nature06738

Nelson, R. J., & Chiavegatto, S. (2001). Molecular basis of aggression. *Trends in Neurosciences*, *24*(12), 713–719. https://doi.org/10.1016/S0166-2236(00)01996-2

Nephew, B. C., & Bridges, R. S. (2008). Central actions of arginine vasopressin and a V1a receptor antagonist on maternal aggression, maternal behavior, and grooming in lactating rats. Pharmacology. *Biochemistry, and Behavior*, *91*(1), 77–83. https://doi.org/10.1016/j.pbb.2008.06.013

Nephew, B. C., Byrnes, E. M., & Bridges, R. S. (2010). Vasopressin mediates enhanced offspring protection in multiparous rats. *Neuropharmacology*, *58*(1), 102–106. https://doi.org/10.1016/j.neuropharm.2009.06.032

Neumann, I. D. (2002). Involvement of the brain oxytocin system in stress coping: Interactions with the hypothalamo-pituitary-adrenal axis. *Progress in Brain Research*, *139*, 147–162. https://doi.org/10.1016/S0079-6123(02)39014-9

Neumann, I. D., Veenema, A. H., & Beiderbeck, D. I. (2010). Aggression and anxiety: Social context and neurobiological links. *Frontiers in Behavioral Neuroscience*, *4*(MAR), 12. https://doi.org/10.3389/fnbeh.2010.00012

Nilsson, S. R., Goodwin, N. L., Choong, J. J., Hwang, S., Wright, H. R., Norville, Z. C., Tong, X., Lin, D., Bentzley, B. S., Eshel, N., McLaughlin, R. J., & Golden, S. A. (2020). Simple Behavioral Analysis (SimBA) – an open source toolkit for computer classification of complex social behaviors in experimental animals. *BioRxiv*, 2020.04.19.049452. https://doi.org/10.1101/2020.04.19.049452

Nomura, M., Durbak, L., Chan, J., Smithies, O., Gustafsson, J.-A., Korach, K. S., Pfaff, D. W., & Ogawa, S. (2002). Genotype/age interactions on aggressive behavior in gonadally intact estrogen receptor β knockout (betaERKO) male mice. *Hormones and Behavior*, *41*(3), 288–296. https://doi.org/10.1006/hbeh.2002.1773

Novick, A. M., Forster, G. L., Hassell, J. E., Davies, D. R., Scholl, J. L., Renner, K. J., & Watt, M. J. (2015). Increased dopamine transporter function as a mechanism for dopamine hypoactivity in the adult infralimbic medial prefrontal cortex following adolescent social stress. *Neuropharmacology*, *97*, 194–200. https://doi.org/10.1016/j.neuropharm.2015.05.032

Ogawa, S., Chan, J., Chester, A. E., Gustafsson, J.-Å., Korach, K. S., & Pfaff, D. W. (1999). Survival of reproductive behaviors in estrogen receptor β gene-deficient (betaERKO) male and female mice. *Proceedings of the*

National Academy of Sciences of the United States of America, *96*(22), 12887–12892. https://doi.org/10.1073/pnas.96.22.12887

Ogawa, S., Eng, V., Taylor, J., Lubahn, D. B., Korach, K. S., & Pfaff, D. W. (1998). Roles of estrogen receptor-α gene expression in reproduction-related behaviors in female mice. *Endocrinology*, *139*(12), 5070–5081. https://doi.org/10.1210/endo.139.12.6357

Ogawa, S., Lubahn, D. B., Korach, K. S., & Pfaff, D. W. (1997). Behavioral effects of estrogen receptor gene disruption in male mice. *Proceedings of the National Academy of Sciences of the United States of America*, *94*(4), 1476–1481. https://doi.org/10.1073/pnas.94.4.1476

Ogawa, S., Washburn, T. F., Taylor, J., Lubahn, D. B., Korach, K. S., & Pfaff, D. W. (1998). Modifications of testosterone-dependent behaviors by estrogen receptor-α gene disruption in male mice. *Endocrinology*, *139*(12), 5058–5069. https://doi.org/10.1210/endo.139.12.6358

Oliveira, V. E. d. M., Lukas, M., Wolf, H. N., Durante, E., Lorenz, A., Mayer, A., Bludau, A., Bosch, O. J., Grinevich, V., Egger, V., de Jong, T., & Neumann, I. D. (2021). Oxytocin and vasopressin within the ventral and dorsal lateral septum modulate aggression in female rats. *Nature Communications*, *12*, 2900. https://doi.org/10.1038/s41467-021-23064-5

Oliveira, V. E. M., Neumann, I. D., & de Jong, T. R. (2019). Post-weaning social isolation exacerbates aggression in both sexes and affects the vasopressin and oxytocin system in a sex-specific manner. *Neuropharmacology*, *156*, 107504. https://doi.org/10.1016/j.neuropharm.2019.01.019

Olivier, B. (2004). Serotonin and aggression. *Annals of the New York Academy of Sciences*, *1036*(1), 382–392. https://doi.org/10.1196/annals.1330.022

Opendak, M., Offit, L., Monari, P., Schoenfeld, T. J., Sonti, A. N., Cameron, H. A., & Gould, E. (2016). Lasting adaptations in social behavior produced by social disruption and inhibition of adult neurogenesis. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *36*(26), 7027–7038. https://doi.org/10.1523/JNEUROSCI.4435-15.2016

Oyegbile, T. O., & Marler, C. A. (2005). Winning fights elevates testosterone levels in California mice and enhances future ability to win fights. *Hormones and Behavior*, *48*(3), 259–267. https://doi.org/10.1016/j.yhbeh.2005.04.007

Parker, K. J., Phillips, K. M., Kinney, L. F., & Lee, T. M. (2001). Day length and sociosexual cohabitation alter central oxytocin receptor binding in female meadow voles (Microtus pennsylvanicus). *Behavioral Neuroscience*, *115*(6), 1349–1356. https://doi.org/10.1037/0735-7044.115.6.1349

Partonen, T., & Lönnqvist, J. (2012). Seasonal affective disorder. *CNS Drugs*, *9*(3), 203–212. 1998 9:3, https://doi.org/10.2165/00023210-199809030-00004

Pawluski, J. L., Li, M., & Lonstein, J. S. (2019). Serotonin and motherhood: From molecules to mood. *Frontiers in Neuroendocrinology*, *53*, 100742. https://doi.org/10.1016/j.yfrne.2019.03.001

Payne, A. P., & Swanson, H. H. (1972). The effect of sex hormones on the agonistic behavior of the male golden hamster (Mesocricetus auratus Waterhouse). *Physiology & Behavior*, *8*(4), 687–691. https://doi.org/10.1016/0031-9384(72)90096-0

Pellis, S. M., & Pellis, V. C. (2017). What is play fighting and what is it good for? *Learning & Behavior*, *45*(4), 355–366. https://doi.org/10.3758/s13420-017-0264-3

Pellis, S. M., Pellis, V. C., & Dewsbury, D. A. (1989). Different levels of complexity in the play-fighting by muroid rodents appear to result from different levels of intensity of attack and defense. *Aggressive Behavior*, *15*(4), 297–310. https://doi.org/10.1002/ab.2480150405

Piña-Andrade, S., Ramos, G., Cárdenas-León, M., Martínez, A., Romero-Morales, L., Martínez-Torres, M., Cedillo-Ildefonso, B., & Luis, J. (2020). Testosterone dependent territorial aggression is modulated by cohabitation with a female in male Mongolian gerbils (Meriones unguiculatus). *Hormones and Behavior*, *117*, 104611. https://doi.org/10.1016/j.yhbeh.2019.104611

Praschak-Rieder, N., Willeit, M., Wilson, A. A., Houle, S., & Meyer, J. H. (2008). Seasonal variation in human brain serotonin transporter binding. *Archives of General Psychiatry*, *65*(9), 1072–1078. https://doi.org/10.1001/archpsyc.65.9.1072

Prendergast, B. J., Zucker, I., & Nelson, R. J. (2002). Seasonal rhythms of mammalian behavioral neuroendocrinology. In D. W. Pfaff, A. M. Etgen, R. T. Rubin, A. P. Arnold, & S. E. Fahrbach (Eds.), *Hormones, brain and behavior* (pp. 507–538). Academic Press.

Pyter, L. M., & Nelson, R. J. (2006). Enduring effects of photoperiod on affective behaviors in Siberian hamsters (Phodopus sungorus). *Behavioral Neuroscience*, *120*(1), 125–134. https://doi.org/10.1037/0735-7044.120.1.125

Raghavendra, V., & Kulkarni, S. K. (2000). Melatonin reversal of DOI-induced hypophagia in rats; possible mechanism by suppressing 5-HT (2A) receptor-mediated activation of HPA axis. *Brain Research*, *860*(1–2), 112–118. https://doi.org/10.1016/S0006-8993(00)02031-X

Ramirez, J. M. (2003). Hormones and aggression in childhood and adolescence. *Aggression and Violent Behavior*, *8*(6), 621–644. https://doi.org/10.1016/S1359-1789(02)00102-7

Ramsteijn, A. S., Van de Wijer, L., Rando, J., van Luijk, J., Homberg, J. R., & Olivier, J. D. A. (2020). Perinatal selective serotonin reuptake inhibitor exposure and behavioral outcomes: A systematic review and meta-analyses of animal studies. *Neuroscience and Biobehavioral Reviews*, *114*, 53–69. https://doi.org/10.1016/j.neubiorev.2020.04.010

Rendon, N. M., & Demas, G. E. (2016). Bi-directional actions of dehydroepiandrosterone and aggression in female Siberian hamsters. *Journal of Experimental Zoology. Part A, Ecological Genetics and Physiology*, *325*(2), 116–121. https://doi.org/10.1002/jez.2001

Rendon, N. M., Petersen, C. L., Munley, K. M., Amez, A. C., Boyes, D. L., Kingsbury, M. A., & Demas, G. E. (2020). Seasonal patterns of melatonin alter aggressive phenotypes of female Siberian hamsters. *Journal of Neuroendocrinology*, *32*(8), e12894. https://doi.org/10.1111/jne.12894

Ricci, L. A., Grimes, J. M., & Melloni, R. H., Jr. (2004). Serotonin type 3 receptors modulate the aggression-stimulating effects of adolescent cocaine exposure in Syrian hamsters (Mesocricetus auratus). *Behavioral Neuroscience*, *118*(5), 1097–1110. https://doi.org/10.1037/0735-7044.118.5.1097

Ricci, L. A., Rasakham, K., Grimes, J. M., & Melloni, R. H., Jr. (2006). Serotonin-1A receptor activity and expression modulate adolescent anabolic/androgenic steroid-induced aggression in hamsters. *Pharmacology, Biochemistry, and Behavior*, *85*(1), 1–11. https://doi.org/10.1016/j.pbb.2006.06.022

Ricci, L. A., Schwartzer, J. J., & Melloni, R. H., Jr. (2009). Alterations in the anterior hypothalamic dopamine system in aggressive adolescent AAS-treated hamsters. *Hormones and Behavior*, *55*(2), 348–355. https://doi.org/10.1016/j.yhbeh.2008.10.011

Rieger, N. S., & Marler, C. A. (2018). The function of ultrasonic vocalizations during territorial defence by pair-bonded male and female California mice. *Animal Behaviour*, *135*, 97–108. https://doi.org/10.1016/j.anbehav.2017.11.008

Romeo, R. D., Schulz, K. M., Nelson, A. L., Menard, T. A., & Sisk, C. L. (2003). Testosterone, puberty, and the pattern of male aggression in Syrian hamsters. *Developmental Psychobiology*, *43*(2), 102–108. https://doi.org/10.1002/dev.10125

Rosenblatt, J. S., Factor, E. M., & Mayer, A. D. (1994). Relationship between maternal aggression and maternal care in the rat. *Aggressive Behavior*, *20*(3), 243–255. https://doi.org/10.1002/1098-2337(1994)20:3<243::AID-AB2480200311>3.0.CO;2-L

Rosvall, K. A., Bergeon Burns, C. M., Barske, J., Goodson, J. L., Schlinger, B. A., Sengelaub, D. R., & Ketterson, E. D. (2012). Neural sensitivity to sex steroids predicts individual differences in aggression: implications for behavioural evolution. *Proceedings. Biological*

Sciences/the Royal Society, *279*(1742), 3547–3555. https://doi.org/10.1098/rspb.2012.0442

Sabihi, S., Dong, S. M., Durosko, N. E., & Leuner, B. (2014). Oxytocin in the medial prefrontal cortex regulates maternal care, maternal aggression and anxiety during the postpartum period. *Frontiers in Behavioral Neuroscience*, *8*, 258. https://doi.org/10.3389/fnbeh.2014.00258

Sachser, N., Hennessy, M. B., & Kaiser, S. (2018). The adaptive shaping of social behavioural phenotypes during adolescence. *Biology Letters*, *14*(11), 20180536. https://doi.org/10.1098/rsbl.2018.0536

Sano, K., Tsuda, M. C., Musatov, S., Sakamoto, T., & Ogawa, S. (2013). Differential effects of site-specific knockdown of estrogen receptor α in the medial amygdala, medial pre-optic area, and ventromedial nucleus of the hypothalamus on sexual and aggressive behavior of male mice. *The European Journal of Neuroscience*, *37*(8), 1308–1319. https://doi.org/10.1111/ejn.12131

Sato, T., Matsumoto, T., Kawano, H., Watanabe, T., Uematsu, Y., Sekine, K., Fukuda, T., Aihara, K-I., Krust, A., Yamada, T., Nakamichi, Y., Yamamoto, Y., Nakamura, T., Yoshimura, K., Yoshizawa, T., Metzger, D., Chambon, P., & Kato, S. (2004). Brain masculinization requires androgen receptor function. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(6), 1673–1678. https://doi.org/10.1073/pnas.0305303101

Sayler, A. (1970). The effect of anti-androgens on aggressive behavior in the gerbil. *Physiology & Behavior*, *5*(6), 667–671. https://doi.org/10.1016/0031-9384(70)90228-3

Schulz, K. M., Zehr, J. L., Salas-Ramirez, K. Y., & Sisk, C. L. (2009). Testosterone programs adult social behavior before and during, but not after, adolescence. *Endocrinology*, *150*(8), 3690–3698. https://doi.org/10.1210/en.2008-1708

Schulz, K. P., Newcorn, J. H., Schmeidler, J., & Halperin, J. M. (2002). Lack of seasonal rhythms in central serotonergic function in boys with ADHD. *Psychoneuroendocrinology*, *27*(4), 463–473. https://doi.org/10.1016/S0306-4530(01)00063-4

Schwartzer, J. J., & Melloni, R. H., Jr. (2010a). Anterior hypothalamic dopamine D2 receptors modulate adolescent anabolic/androgenic steroid-induced offensive aggression in the Syrian hamster. *Behavioural Pharmacology*, *21*(4), 314–322. https://doi.org/10.1097/FBP.0b013e32833b10f1

Schwartzer, J. J., & Melloni, R. H., Jr. (2010b). Dopamine activity in the lateral anterior hypothalamus modulates AAS-induced aggression through D2 but not D5 receptors. *Behavioral Neuroscience*, *124*(5), 645–655. https://doi.org/10.1037/a0020899

Scordalakes, E. M., & Rissman, E. F. (2003). Aggression in male mice lacking functional estrogen receptor α. *Behavioral Neuroscience*, *117*(1), 38–45. https://doi.org/10.1037/0735-7044.117.1.38

Scott, J. P. (1966). Agonistic behavior of mice and rats: A review. *Integrative and Comparative Biology*, *6*(4), 683–701. https://doi.org/10.1093/icb/6.4.683

Scotti, M.-A. L., Rendon, N. M., Greives, T. J., Romeo, R. D., & Demas, G. E. (2015). Short-day aggression is independent of changes in cortisol or glucocorticoid receptors in male Siberian hamsters (Phodopus sungorus). *Journal of Experimental Zoology. Part A, Ecological Genetics and Physiology*, *323*(5), 331–341. https://doi.org/10.1002/jez.1922

Shih, J. C., Ridd, M. J., Chen, K., Meehan, W. P., Kung, M. P., Seif, I., & De Maeyer, E. (1999). Ketanserin and tetrabenazine abolish aggression in mice lacking monoamine oxidase A. *Brain Research*, *835*(2), 104–112. https://doi.org/10.1016/S0006-8993(99)01478-X

Shin, S. Y., Baek, N. J., Han, S. H., & Min, S. S. (2019). Chronic administration of ketamine ameliorates the anxiety- and aggressive-like behavior in adolescent mice induced by neonatal maternal separation. *The Korean Journal of Physiology & Pharmacology*, *23*(1), 81–87. https://doi.org/10.4196/kjpp.2019.23.1.81

Silva, A. L., Fry, W. H. D., Sweeney, C., & Trainor, B. C. (2010). Effects of photoperiod and experience on aggressive behavior in female California mice. *Behavioural Brain Research*, *208*(2), 528–534. https://doi.org/10.1016/j.bbr.2009.12.038

Simerly, R. B., Chang, C., Muramatsu, M., & Swanson, L. W. (1990). Distribution of androgen and estrogen receptor mRNA-containing cells in the rat brain: An in situ hybridization study. *The Journal of Comparative Neurology*, *294*(1), 76–95. https://doi.org/10.1002/cne.902940107

Simon, J. A. (2002). Estrogen replacement therapy: Effects on the endogenous androgen milieu. *Fertility and Sterility*, *77*(Suppl. 4), S77–S82. https://doi.org/10.1016/S0015-0282(02)02986-2

Smith, C. J. W., DiBenedictis, B. T., & Veenema, A. H. (2019). Comparing vasopressin and oxytocin fiber and receptor density patterns in the social behavior neural network: Implications for cross-system signaling. *Frontiers in Neuroendocrinology*, *53*, 100737. https://doi.org/10.1016/j.yfrne.2019.02.001

Smith, C. J. W., Poehlmann, M. L., Li, S., Ratnaseelan, A. M., Bredewold, R., & Veenema, A. H. (2017). Age and sex differences in oxytocin and vasopressin V1a receptor binding densities in the rat brain: Focus on the social decision-making network. *Brain Structure & Function*, *222*(2), 981–1006. https://doi.org/10.1007/s00429-016-1260-7

So, N., Franks, B., Lim, S., & Curley, J. P. (2015). A social network approach reveals associations between mouse social dominance and brain gene expression. *PLoS ONE*, *10*(7), e0134509. https://doi.org/10.1371/journal.pone.0134509

Soma, K. K. (2006). Testosterone and aggression: Berthold, birds and beyond. *Journal of Neuroendocrinology*, *18*(7), 543–551. https://doi.org/10.1111/j.1365-2826.2006.01440.x

Soma, K. K., Rendon, N. M., Boonstra, R., Albers, H. E., & Demas, G. E. (2015). DHEA effects on brain and behavior: Insights from comparative studies of aggression. *The Journal of Steroid Biochemistry and Molecular Biology*, *145*, 261–272. https://doi.org/10.1016/j.jsbmb.2014.05.011

Soma, K. K., Scotti, M. A., Newman, A. E., Charlier, T. D., & Demas, G. E. (2008). Novel mechanisms for neuroendocrine regulation of aggression. *Frontiers in Neuroendocrinology*, *29*(4), 476–489. https://doi.org/10.1016/j.yfrne.2007.12.003

Song, Z., & Albers, H. E. (2018). Cross-talk among oxytocin and arginine-vasopressin receptors: Relevance for basic and clinical studies of the brain and periphery. *Frontiers in Neuroendocrinology*, *51*, 14–24. https://doi.org/10.1016/j.yfrne.2017.10.004

Spear, L. P. (2000). Neurobehavioral changes in adolescence. *Current Directions in Psychological Science*, *9*(4), 111–114. https://doi.org/10.1111/1467-8721.00072

Spies, M., James, G. M., Vraka, C., Philippe, C., Hienert, M., Gryglewski, G., Komorowski, A., Kautzky, A., Silberbauer, L., Pichler, V., Kranz, G. S., Nics, L., Balber, T., Baldinger-Melich, P., Vanicek, T., Spurny, B., Winkler-Pjrek, E., Wadsak, W., Mitterhauser, M., . . . Winkler, D. (2018). Brain monoamine oxidase A in seasonal affective disorder and treatment with bright light therapy. *Translational Psychiatry*, *8*(1), 1–9. https://doi.org/10.1038/s41398-018-0227-2

Spindelegger, C., Stein, P., Wadsak, W., Fink, M., Mitterhauser, M., Moser, U., Savli, M., Mien, L.-K., Akimova, E., Hahn, A., Willeit, M., Kletter, K., Kasper, S., & Lanzenberger, R. (2012). Light-dependent alteration of serotonin-1A receptor binding in cortical and subcortical limbic regions in the human brain. *The World Journal of Biological Psychiatry*, *13*(6), 413–422. https://doi.org/10.3109/15622975.2011.630405

Stribley, J. M., & Carter, C. S. (1999). Developmental exposure to vasopressin increases aggression in adult prairie voles. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(22), 12601–12604. https://doi.org/10.1073/pnas.96.22.12601

Susman, E. J., Inoff-Germain, G., Nottelmann, E. D., Loriaux, D. L., Cutler, G. B., Jr., & Chrousos, G. P. (1987). Hormones, emotional dispositions, and aggressive attributes in young adolescents. *Child Development*, *58*(4), 1114–1134. https://doi.org/10.2307/1130551

Svirsky, N., Levy, S., & Avitsur, R. (2016). Prenatal exposure to selective serotonin reuptake inhibitors (SSRI) increases aggression and modulates maternal behavior in offspring mice. *Developmental Psychobiology*, *58*(1), 71–82. https://doi.org/10.1002/dev.21356

Takahashi, A., & Miczek, K. A. (2014). Neurogenetics of aggressive behavior: Studies in rodents. *Current Topics in Behavioral Neurosciences*, *17*, 3–44. https://doi.org/10.1007/7854_2013_263

Takahashi, A., Quadros, I. M., de Almeida, R. M. M., & Miczek, K. A. (2011). Brain serotonin receptors and transporters: Initiation vs. termination of escalated aggression. *Psychopharmacology*, *213*(2–3), 183–212. https://doi.org/10.1007/s00213-010-2000-y

Takahashi, L. K., Thomas, D. A., & Barfield, R. J. (1983). Analysis of ultrasonic vocalizations emitted by residents during aggressive encounters among rats (Rattus norvegicus). *Journal of Comparative Psychology*, *97*(3), 207–212. https://doi.org/10.1037/0735-7036.97.3.207

Taravosh-Lahn, K., Bastida, C., & Delville, Y. (2006). Differential responsiveness to fluoxetine during puberty. *Behavioral Neuroscience*, *120*(5), 1084–1092. https://doi.org/10.1037/0735-7044.120.5.1084

Taylor, G. T., Haller, J., Rupich, R., & Weiss, J. (1984). Testicular hormones and intermale aggressive behaviour in the presence of a female rat. *The Journal of Endocrinology*, *100*(3), 315–321. https://doi.org/10.1677/joe.0.1000315

Terranova, J. I., Ferris, C. F., & Albers, H. E. (2017). Sex differences in the regulation of offensive aggression and dominance by arginine-vasopressin. *Frontiers in Endocrinology*, *8*(Nov.), 308. https://doi.org/10.3389/fendo.2017.00308

Tielbeek, J. J., Al-Itejawi, Z., Zijlmans, J., Polderman, T. J., Buckholtz, J. W., & Popma, A. (2018). The impact of chronic stress during adolescence on the development of aggressive behavior: A systematic review on the role of the dopaminergic system in rodents. *Neuroscience and Biobehavioral Reviews*, *91*, 187–197. https://doi.org/10.1016/j.neubiorev.2016.10.009

Timmer, M., Cordero, M. I., Sevelinges, Y., & Sandi, C. (2011). Evidence for a role of oxytocin receptors in the long-term establishment of dominance hierarchies. *Neuropsychopharmacology*, *36*(11), 2349–2356. https://doi.org/10.1038/npp.2011.125

Trainor, B. C., & Marler, C. A. (2001). Testosterone, paternal behavior, and aggression in the monogamous California mouse (Peromyscus californicus). *Hormones and Behavior*, *40*(1), 32–42. https://doi.org/10.1006/hbeh.2001.1652

Trainor, B. C., Bird, I. M., & Marler, C. A. (2004). Opposing hormonal mechanisms of aggression revealed through short-lived testosterone manipulations and multiple winning experiences. *Hormones and Behavior*, *45*(2), 115–121. https://doi.org/10.1016/j.yhbeh.2003.09.006

Trainor, B. C., Finy, M. S., & Nelson, R. J. (2008). Rapid effects of estradiol on male aggression depend on photoperiod in reproductively nonresponsive mice. *Hormones and Behavior*, *53*(1), 192–199. https://doi.org/10.1016/j.yhbeh.2007.09.016

Trainor, B. C., Greiwe, K. M., & Nelson, R. J. (2006). Individual differences in estrogen receptor α in select brain nuclei are associated with individual differences in aggression. *Hormones and Behavior*, *50*(2), 338–345. https://doi.org/10.1016/j.yhbeh.2006.04.002

Trainor, B. C., Sisk, C. L., & Nelson, R. J. (2009). 5-Hormones and the development and expression of aggressive behavior. In D. W. Pfaff, A. P. Arnold, A. M. Etgen, S. E. Fahrbach & R. T. Rubin (Eds.), *Hormones, brain and behavior* (2nd ed., pp. 167–205). Academic Press. https://doi.org/10.1016/B978-008088783-8.00005-X

Tricklebank, M. D., & Petrinovic, M. M. (2019). Serotonin and aggression. In M. D. Tricklebank & e. Daly (Eds.), The serotonin system (pp. 155–180). Elsevier. https://doi.org/10.1016/B978-0-12-813323-1.00009-8

Tsuda, M. C., Yamaguchi, N., & Ogawa, S. (2011). Early life stress disrupts peripubertal development of aggression in male mice. *Neuroreport*, *22*(6), 259–263. https://doi.org/10.1097/WNR.0b013e328344495a

Unger, E. K., Burke, K. J., Fuller, P. M., & Shah, N. M. (2014). Medial Amygdalar Aromatase Neurons Regulate Aggression in Both Sexes. https://doi.org/10.1016/j.celrep.2014.12.040

Unger, E. K., Burke, K. J., Jr., Yang, C. F., Bender, K. J., Fuller, P. M., & Shah, N. M. (2015). Medial amygdalar aromatase neurons regulate aggression in both sexes. *Cell Reports*, *10*(4), 453–462. https://doi.org/10.1016/j.celrep.2014.12.040

van den Berg, C. L., Hol, T., Van Ree, J. M., Spruijt, B. M., Everts, H., & Koolhaas, J. M. (1999). Play is indispensable for an adequate development of coping with social challenges in the rat. *Developmental Psychobiology*, *34*(2), 129–138. https://doi.org/10.1002/(SICI)1098-2302(199903)34:2<129::AID-DEV6>3.0.CO;2-L

Vanderschuren, L. J. M. J., Achterberg, E. J. M., & Trezza, V. (2016). The neurobiology of social play and its rewarding value in rats. *Neuroscience and Biobehavioral Reviews*, *70*, 86–105. https://doi.org/10.1016/j.neubiorev.2016.07.025

Veenema, A. H., & Neumann, I. D. (2009). Maternal separation enhances offensive play-fighting, basal corticosterone and hypothalamic vasopressin mRNA expression in juvenile male rats. *Psychoneuroendocrinology*, *34*(3), 463–467. https://doi.org/10.1016/j.psyneuen.2008.10.017

Veenema, A. H., Beiderbeck, D. I., Lukas, M., & Neumann, I. D. (2010). Distinct correlations of vasopressin release within the lateral septum and the bed nucleus of the stria terminalis with the display of intermale aggression. *Hormones and Behavior*, *58*(2), 273–281. https://doi.org/10.1016/j.yhbeh.2010.03.006

Veiga, C. P., Miczek, K. A., Lucion, A. B., & Almeida, R. M. (2007). Effect of 5-HT1B receptor agonists injected into the prefrontal cortex on maternal aggression in rats. *Brazilian Journal of Medical and Biological Research*, *40*(6), 825–830. https://doi.org/10.1590/S0100-879X2006005000113

Walker, S. E., Papilloud, A., Huzard, D., & Sandi, C. (2018). The link between aberrant hypothalamic-pituitary-adrenal axis activity during development and the emergence of aggression-Animal studies. *Neuroscience and Biobehavioral Reviews*, *91*, 138–152. https://doi.org/10.1016/j.neubiorev.2016.10.008

Wallis, C. J., & Luttge, W. G. (1975). Maintenance of male sexual behavior by combined treatment with oestrogen and dihydrotestosterone in CD-1 mice. *The Journal of Endocrinology*, *66*(2), 257–262. https://doi.org/10.1677/joe.0.0660257

Walton, J. C., Weil, Z. M., & Nelson, R. J. (2011). Influence of photoperiod on hormones, behavior, and immune function. *Frontiers in Neuroendocrinology*, *32*(3), 303–319. https://doi.org/10.1016/j.yfrne.2010.12.003

Walton, K. D., Lieberman, D., Llinás, A., Begin, M., & Llinás, R. R. (1992). Identification of a critical period for motor development in neonatal rats. *Neuroscience*, *51*(4), 763–767. https://doi.org/10.1016/0306-4522(92)90517-6

Wang, J., Tai, F., Yan, X., & Yu, P. (2012). Paternal deprivation alters play-fighting, serum corticosterone and the expression of hypothalamic vasopressin and oxytocin in juvenile male mandarin voles. *Journal of Comparative Physiology A*, *198*(11), 787–796. https://doi.org/10.1007/s00359-012-0748-8

Watt, M. J., Burke, A. R., Renner, K. J., & Forster, G. L. (2009). Adolescent male rats exposed to social defeat exhibit altered anxiety behavior and limbic monoamines as adults. *Behavioral Neuroscience*, *123*(3), 564–576. https://doi.org/10.1037/a0015752

Wersinger, S. R., Caldwell, H. K., Christiansen, M., & Young, W. S., III (2007). Disruption of the vasopressin 1b receptor gene impairs the attack component of aggressive behavior in mice. *Genes Brain & Behavior*, *6*(7), 653–660. https://doi.org/10.1111/j.1601-183X.2006.00294.x

Wersinger, S. R., Caldwell, H. K., Martinez, L., Gold, P., Hu, S. B., & Young, W. S., III (2007). Vasopressin 1a receptor knockout mice have a subtle olfactory deficit but normal aggression. *Genes Brain & Behavior*, *6*(6), 540–551. https://doi.org/10.1111/j.1601-183X.2006.00281.x

Williamson, C. M., Franks, B., & Curley, J. P. (2016). Mouse social network dynamics and community structure are associated with plasticity-related brain gene expression. *Frontiers in Behavioral Neuroscience*, *10*, Article PMC4972826. https://doi.org/10.3389/fnbeh.2016.00152

Williamson, C. M., Lee, W., DeCasien, A. R., Lanham, A., Romeo, R. D., & Curley, J. P. (2019). Social hierarchy position in female mice is associated with plasma corticosterone levels and hypothalamic gene expression. *Scientific Reports*, *9*(1), 7324. https://doi.org/10.1038/s41598-019-43747-w

Williamson, C. M., Romeo, R. D., & Curley, J. P. (2017). Dynamic changes in social dominance and mPOA GnRH expression in male mice following social opportunity. *Hormones and Behavior*, *87*, 80–88. https://doi.org/10.1016/J.YHBEH.2016.11.001

Winslow, J. T., Hastings, N., Carter, C. S., Harbaugh, C. R., & Insel, T. R. (1993). A role for central vasopressin in pair bonding in monogamous prairie voles. *Nature*, *365*(6446), 545–548. https://doi.org/10.1038/365545a0

Wolff, J. O. (1985). Maternal aggression as a deterrent to infanticide in Peromyscus leucopus and P. maniculatus. *Animal Behaviour*, *33*(1), 117–123. https://doi.org/10.1016/S0003-3472(85)80125-1

Wommack, J. C., & Delville, Y. (2007a). Cortisol controls the pubertal development of agonistic behavior in male golden hamsters via type II corticosteroid receptors. *Hormones and Behavior*, *51*(3), 306–312. https://doi.org/10.1016/j.yhbeh.2006.11.007

Wommack, J. C., & Delville, Y. (2007b). Stress, aggression, and puberty: Neuroendocrine correlates of the development of agonistic behavior in golden hamsters. *Brain, Behavior and Evolution*, *70*(4), 267–273. https://doi.org/10.1159/000105490

Wommack, J. C., Salinas, A., & Delville, Y. (2005). Glucocorticoids and the development of agonistic behaviour during puberty in male golden hamsters. *Journal of Neuroendocrinology*, *17*(12), 781–787. https://doi.org/10.1111/j.1365-2826.2005.01369.x

Wood, R. (1995). Androgen and estrogen receptors coexist within individual neurons in the brain of the Syrian hamster. https://www.karger.com/Article/Abstract/127039 https://doi.org/10.1159/000127039

Wright, E. C., Culkin, H. I., Sekar, S., Kapoor, A., Corbett, C., & Trainor, B. C. (2020). Pubertal androgens reduce the effects of social stress on anxiety-related behaviors in California mice. *BioRxiv*, 2020.12.02.408526. https://doi.org/10.1101/2020.12.02.408526

Young, L. J., Winslow, J. T., Nilsen, R., & Insel, T. R. (1997). Species differences in V1a receptor gene expression in monogamous and nonmonogamous voles: Behavioral consequences. *Behavioral Neuroscience*, *111*(3), 599–560. 5. https://doi.org/10.1037/0735-7044.111.3.599

Yu, Q., Teixeira, C. M., Mahadevia, D., Huang, Y., Balsam, D., Mann, J. J., Gingrich, J. A., & Ansorge, M. S. (2014). Dopamine and serotonin signaling during two sensitive developmental periods differentially impact adult aggressive and affective behaviors in mice. *Molecular Psychiatry*, *19*(6), 688–698. https://doi.org/10.1038/mp.2014.10

Zhao, C., Chang, L., Auger, A. P., Gammie, S. C., & Riters, L. V. (2020). Mu opioid receptors in the medial preoptic area govern social play behavior in adolescent male rats. *Genes Brain & Behavior*, *19*(7), e12662. https://doi.org/10.1111/gbb.12662

Zheng, D. J., Singh, A., & Phelps, S. M. (2021). Conservation and dimorphism in androgen receptor distribution in Alston's singing mouse (Scotinomys teguina). *The Journal of Comparative Neurology*, *529*(10), 2539–2557. https://doi.org/10.1002/cne.25108

Received August 5, 2021
Revision received November 30, 2021
Accepted December 7, 2021 ■