Received: 26 January 2022 | Revised: 16 March 2022 | Accepted: 7 April 2022

DOI: 10.1002/jez.2601

REVIEW

JEZ-A ECOLOGICAL AND INTEGRATIVE PHYSIOLOGY WILEY

Winter madness: Melatonin as a neuroendocrine regulator of seasonal aggression

Kathleen M. Munley | Yuqi Han | Matt X. Lansing | Gregory E. Demas

Department of Biology and Center for the Integrative Study of Animal Behavior, Indiana University, Bloomington, Indiana, USA

Correspondence
Kathleen M. Munley, Department of Biology, Indiana University, 1001 East Third Street, Bloomington, IN 47405, USA.
Email: kmunley@indiana.edu

Funding information
Indiana Academy of Sciences, Grant/Award Number: Senior Research Grant; Indiana University Bloomington, Grant/Award Numbers: CISAB Predoctoral Fellowship, COAS Dissertation Research Fellowship, and Louise Constable Hoover Fellowship, Center for the Integrative Study of Behavior Predoctoral Fellowship, College of Arts and Sciences Dissertation Research Fellowship, and Department of Biology Louise Constable Hoover Fellowship; National Science Foundation, Grant/Award Number: IOS-1656414; National Institute of Child Health and Human Development, Grant/Award Number: T32HD049336; National Institute of Mental Health, Grant/Award Number: R21MH109942

Abstract

Individuals of virtually all vertebrate species are exposed to annual fluctuations in the deterioration and renewal of their environments. As such, organisms have evolved to restrict energetically expensive processes and activities to a specific time of the year. Thus, the precise timing of physiology and behavior is critical for individual reproductive success and subsequent fitness. Although the majority of research on seasonality has focused on seasonal reproduction, pronounced fluctuations in other non-reproductive social behaviors, including agonistic behaviors (e.g., aggression), also occur. To date, most studies that have investigated the neuroendocrine mechanisms underlying seasonal aggression have focused on the role of photoperiod (i.e., day length); prior findings have demonstrated that some seasonally breeding species housed in short "winter-like" photoperiods display increased aggression compared with those housed in long "summer-like" photoperiods, despite inhibited reproduction and low gonadal steroid levels. While fewer studies have examined how the hormonal correlates of environmental cues regulate seasonal aggression, our previous work suggests that the pineal hormone melatonin acts to increase non-breeding aggression in Siberian hamsters (*Phodopus sungorus*) by altering steroid hormone secretion. This review addresses the physiological and cellular mechanisms underlying seasonal plasticity in aggressive and non-aggressive social behaviors, including a key role for melatonin in facilitating a "neuroendocrine switch" to alternative physiological mechanisms of aggression across the annual cycle. Collectively, these studies highlight novel and important mechanisms by which melatonin regulates aggressive behavior in vertebrates and provide a more comprehensive understanding of the neuroendocrine bases of seasonal social behaviors broadly.

KEYWORDS
biological rhythms, microbiome, neurosteroids, pineal, territoriality, violence

1 | INTRODUCTION: A PRIMER ON SEASONALITY

Many non-tropical animals face marked fluctuations in environmental conditions, including changes in photoperiod (i.e., day length), ambient temperature, and food availability, across the annual cycle (Bronson & Heideman, 1994; Stevenson et al., 2017). Consequently, most animals have evolved a wide range of physiological and behavioral adaptations in response to seasonal variation in their environment, including changes in energy balance, immune function, reproduction, and social behavior (reviewed in Bartness et al., 2002; Bronson & Heideman, 1994; Nelson et al., 2002). Such adaptations

allow individuals to prioritize investing in reproduction or survival based on the time of year (Bronson & Heideman, 1994; reviewed in Stearns, 2000; Whittier & Crews, 1987). Thus, physiological mechanisms and behaviors that enhance an individual's chances of reproductive success (e.g., courtship displays, sexual behavior, parental care) are prioritized during the summer months, when biotic and abiotic resources are abundant; whereas mechanisms that promote survival, many of which involve a shift in energy allocation from nonessential functions (e.g., reproduction) to functions that are critical for immediate survival (e.g., gonadal regression, changes in thermoregulation, food hoarding, hibernation), emerge during the winter months, which are often characterized by harsh environmental conditions and a relative scarcity of resources (reviewed in Walton et al., 2011; Wilsterman et al., 2019).

To coordinate these seasonal changes in physiology and behavior with the appropriate time of the year, animals rely on both proximate and ultimate cues in their native environment. Proximate cues (e.g., photoperiod) allow individuals to predict optimal times of the year well in advance of their occurrence, whereas ultimate cues (e.g., food availability) enable individuals to fine-tune these adaptations based on environmental variation that occurs on an acute timescale. Of these factors, most non-tropical species rely primarily on photoperiod as a precise temporal cue to estimate the time of year (reviewed in Goldman, 2001; Stevenson et al., 2017; Walton et al., 2011). In mammals, these photoperiodic responses are mediated by a neural circuit that conveys photic information from the retina to the pineal gland, which culminates in changes in the pattern of secretion of the hormone melatonin (reviewed in Bartness et al., 1993; Goldman, 2001; see also Section 3). Thus, changes in the duration of melatonin secretion influence seasonal plasticity in physiology and behavior. For example, rodents housed in short "winter-like" photoperiods, which are characterized by a long duration of melatonin secretion, undergo gonadal regression, as well as changes in body mass, thermoregulation, and social behavior. Animals maintained in short-day photoperiods for prolonged periods of time (i.e., >15 weeks), however, undergo "spontaneous recrudescence," during which the testes return to their long-day condition and reproduction resumes (Gorman & Zucker, 1995; reviewed in Nicholls et al., 1988).

While the neuroendocrine processes regulating seasonal reproduction and its associated behaviors are well-characterized, less is known about the mechanisms underlying seasonal variation in other social behaviors, such as aggression. In this review, we summarize research that has examined the neuroendocrine basis of seasonal social behaviors in vertebrates. First, we discuss studies that have investigated how seasonal changes in photoperiod affect territorial aggression, specifically by acting via gonadal or extra-gonadal steroid hormones. Next, we highlight research that has assessed the role of melatonin in regulating aggressive and non-aggressive social behaviors, including evidence that melatonin acts indirectly via steroid hormones to facilitate a "seasonal switch" in the neuroendocrine regulation of aggression. Finally, we draw parallels between the seasonal regulation of agonistic and affective behaviors in animal models and humans and propose future directions for this area of research, including pineal modulation of seasonal social behaviors via the gut microbiome. Collectively, this research provides important insight into how melatonin contributes to vertebrate aggression and enhances our understanding of how hormones regulate seasonal plasticity in social behavior.

2 | PHOTOPERIODIC REGULATION OF SEASONAL AGGRESSION

Aggression is perhaps the most well-studied non-reproductive social behavior that has been investigated in a seasonal context. Aggressive behavior is exhibited across animal taxa and enables individuals to compete for access to limited resources in their environment (e.g., territories, food, and mates; Jalabert et al., 2018; Nelson, 2006). Thus, aggression can be displayed by male or female conspecifics or by members of different species. Aggression can be further classified based on the social context in which it is displayed; some of the most extensively investigated subtypes of aggression include inter-male aggression, territorial defense, predatory aggression, and maternal aggression (Brain, 1979; Moyer, 1971; reviewed in Scott, 1966). Because aggressive encounters are a costly investment with respect to energy, predation risk, and physical injury, individuals must evaluate the costs and benefits of competing for these resources and make a decision that results in maximal fitness.

Consequently, many species display high levels of aggression during the breeding season, when competition for access to these resources is considerable and the ability to acquire a mate and actively defend a territory is critical to increasing an individual's chances of reproductive success. Therefore, the role of gonadal steroids in regulating aggressive behavior has been an active area of research for several decades, particularly for animals in breeding condition (reviewed in Albers et al., 2002; Cunningham et al., 2012). Interestingly, some animals exhibit equivalent or higher levels of aggression during the non-breeding season, despite gonadal regression, suggesting that these species face additional selective pressures that favored the evolution of alternative neuroendocrine mechanisms, which are independent of gonadal steroids, to regulate aggressive behavior year-round (reviewed in Munley et al., 2018; Soma et al., 2008). Such species have been particularly useful for studying seasonal and hormonal influences on aggression, as these animals provide an opportunity to explore the role of extra-gonadal steroids, such as adrenal steroids and neurosteroids, in modulating seasonal aggression in an ecologically relevant context.

Because most seasonally breeding animals use photoperiod to anticipate changes in the annual cycle and alter their physiology and behavior accordingly, the majority of studies that have examined seasonal plasticity in aggressive behavior have used experimentally induced or ambient changes in light cycle to measure seasonal changes in this behavior and its underlying mechanisms. In laboratory settings, animals are typically housed in experimental light cycles that simulate seasonal variation in their natural environment; long-day (LD) photoperiods are characteristic of the summer breeding season,

whereas short-day (SD) photoperiods reflect the winter non-breeding season. Conversely, field studies rely on ambient changes in season, enabling researchers to investigate naturally occurring variation in the neuroendocrine regulation of aggression. Although there are several hormones and neuromodulators that regulate aggressive behavior, we will focus our discussion on one class of hormones that has been investigated extensively in neuroendocrine studies of seasonal aggression: steroid hormones.

2.1 | Gonadal steroids

Since Arnold Berthold's discovery of the blood-borne gonadal steroid testosterone (T) and its role in regulating "male-typical" behaviors (e.g., aggression and mating) in male chickens was published nearly 60 years ago (Quiring, 1944), many studies have shown that circulating gonadal steroids are positively associated with aggression during the breeding season (reviewed in Albers et al., 2002; Cunningham et al., 2012). Specifically, studies in red-winged blackbirds (*Agelaius phoeniceus*), Japanese quail (*Coturnix japonica*), green anoles (*Anolis carolinensis*), mountain spiny lizards (*Sceloporus jarrovi*), Mongolian gerbils (*Meriones unguiculatus*), and Campbell's dwarf hamsters (*Phodopus campbelli*) have demonstrated that castration decreases inter-male aggression in a reproductive context, but that this response can be alleviated by exogenous T administration (Adkins & Schlesinger, 1979; Harding et al., 1988; Hume & Wynne-Edwards, 2005; Moore, 1988; Sayler, 1970; Tsutsui & Ishii, 1981; Yahr et al., 1977). A correlation between gonadal steroids and aggression is further supported by studies of inter-male aggression in non-seasonal domesticated rodents, such as laboratory rats (*Rattus norvegicus*) and house mice (*Mus musculus*). In these species, removal of the gonads results in substantial decreases in circulating T and, subsequently, reduced aggression (Edwards, 1969, 1970; reviewed in Haug et al., 1986). Moreover, wild and laboratory male house mice with higher endogenous concentrations of T display greater aggression toward conspecifics and exhibit dominance over animals with lower circulating T levels (Hiadlovská et al., 2015; Williamson et al., 2017), suggesting a potential relationship between circulating androgens and social rank.

While these studies support a role for gonadal steroids in regulating aggressive behavior, this widely accepted relationship is based primarily on studies of male–male aggression in a relatively limited number of species, many of which are domesticated and/or non-seasonal (e.g., laboratory rats and house mice). Indeed, there is considerable evidence that lower circulating T levels are not always associated with reduced aggression, particularly when seasonal and non-domesticated species are examined (e.g., Caldwell et al., 1984; Wiley & Goldizen, 2003). For example, several species of animals do not display decreased aggression after castration during the breeding season, including prairie voles (*Microtus ochrogaster*), Syrian hamsters (*Mesocricetus auratus*), Siberian hamsters (*Phodopus sungorus*), blind mole rats (*Spalax ehrenbergi*), saddle-back tamarins (*Saguinus fuscicollis*), European starlings (*Sturnus vulgaris*), red-sided garter snakes (*Thamnophis sirtalis*), Siamese fighting fish (*Betta splendens*), and threespine stickleback (*Gasterosteus aculeatus*) (Baggerman, 1966; Camazine et al., 1980; Davis, 1957; Demas et al., 1999; Epple, 1978; Gottreich et al., 2001; Scotti et al., 2008; Tiefer, 1970; Weiss & Coughlin, 1979). Collectively, these findings indicate that, although gonadal steroids may regulate breeding aggression in some species, additional extra-gonadal factors are also important in modulating this behavior.

2.2 | Extra-gonadal steroids

In contrast to research that has examined the neuroendocrine basis of breeding aggression, there is little evidence that gonadal steroids regulate non-breeding aggression. Such results are particularly apparent in seasonally breeding species that display equal or higher levels of aggressive behavior during the non-breeding season, despite low circulating gonadal steroid levels. For example, T implantation has no effect on aggression in castrated male long-tailed hamsters (*Tscheskia triton*) housed in SD photoperiods (Wang et al., 2012). In male and female Syrian and Siberian hamsters, which show higher levels of aggression when housed in SD photoperiods compared to LD photoperiods (Badura & Nunez, 1989; Garrett & Campbell, 1980; Jasnow et al., 2000; Scotti et al., 2007), gonadectomy of LD hamsters does not result in SD-like levels of aggression, nor does it block SD-induced increases in aggression (Fleming et al., 1988; Scotti et al., 2007, 2008). In addition, T implants do not elevate aggression in male and female Siberian hamsters (Scotti et al., 2007, 2008), suggesting that photoperiodic effects on aggression are not mediated by gonadal steroid hormones in these species. Some field studies also support a lack of a relationship between gonadal steroids and non-breeding aggression. Male rat-like hamsters (*Cricetus triton*) show elevated aggression during the non-breeding season, despite low levels of T (Zhang et al., 2001), and male wood rats (*Neotoma fuscipes*) exhibit seasonal changes in aggression independent of changes in circulating T (Caldwell et al., 1984). Furthermore, aggressive behavior and T concentrations are positively correlated during the breeding season in male ring-tailed lemurs (*Lemur catta*), but are not correlated during the non-breeding season (Cavigelli & Pereira, 2000). Collectively, these laboratory and field studies strongly suggest that alternative neuroendocrine processes, which are independent of gonadal steroids, regulate non-breeding aggression in some seasonally breeding animals.

In recent years, it has become increasingly clear that extra-gonadal steroids, both in the periphery and in the brain, modulate seasonal aggression in vertebrates (reviewed in Munley et al., 2018; Soma et al., 2008). In particular, the adrenal androgen dehydroepiandrosterone (DHEA) and neurosteroids have emerged as important regulators of non-breeding aggression, mostly from studies conducted in songbirds and rodents. Within the brain, hormonal regulation of aggression has mainly been examined within nodes of the social behavior network, a collection of reciprocally connected nuclei in the basal forebrain, hypothalamus, and midbrain of vertebrates that are sensitive to steroid hormones (reviewed in

Crews, 2003; Goodson, 2005; Newman, 1999; O'Connell & Hofmann, 2011). Of these regions, the anterior hypothalamus (AH), bed nucleus of the stria terminalis (BNST), lateral septum (LS), medial amygdala (MeA), periaqueductal gray (PAG), preoptic area (POA), and ventromedial hypothalamus (VMH) and their non-mammalian homologs have been shown to be associated with aggressive behavior and, thus, have been the primary focus of studies investigating the role of neurosteroids in mediating seasonal aggression. Together, both adrenal and neural steroids likely regulate aggression during the non-breeding season, particularly in seasonally breeding animals that are highly aggressive year-round.

2.2.1 | Adrenal DHEA

DHEA is an androgen that is secreted by the adrenal glands and a few other extra-gonadal tissues, including the liver, gastrointestinal tract, gonads, and brain (Norris & Carr, 2020; reviewed in Prough et al., 2016). While DHEA itself can bind with low affinity to androgen (AR) and estrogen receptors (ERα and ERβ), it predominantly serves as a prohormone and can be metabolized into more potent androgens (e.g., T), and estrogens (e.g., 17β-estradiol [E_2]) via a multi-step reaction in tissues that express the appropriate steroidogenic enzymes (Beck & Handa, 2004; reviewed in Labrie et al., 2005). Importantly, although DHEA is primarily synthesized by peripheral tissues, circulating DHEA (and DHEA sulfate) is capable of passing through the blood–brain barrier and can be converted to other androgens and estrogens within the brain. Due to its low affinity for AR and ERs, high endogenous levels of DHEA would be required to activate these receptors and induce changes in social behavior (reviewed in Prough et al., 2016; Webb et al., 2006). Thus, it is likely that the local metabolism of circulating and/or neurally-synthesized DHEA into more potent androgens and estrogens is responsible for modulating the neural circuits relevant to aggression during the non-breeding season.

Prior studies in seasonally breeding songbirds and rodents suggest a role for adrenal DHEA in regulating non-breeding aggression. In song sparrows (*Melospiza melodia*) and spotted antbirds (*Hylophylax n. naevioides*), two species that display high levels of territorial aggression year-round (Willis, 1972; Wingfield & Hahn, 1994), non-breeding males have lower plasma T and E_2 levels, but higher plasma DHEA levels than breeding males (Hau & Beebe, 2011; Hau et al., 2004; A. E. Newman & Soma, 2009; Soma & Wingfield, 2001). Moreover, circulating DHEA concentrations are positively correlated with aggressive vocalizations displayed during a simulated territorial intrusion (STI) in male spotted antbirds (Hau et al., 2004) and DHEA administration increases STI-induced aggressive behavior and song production in non-breeding male song sparrows (Soma et al., 2002; Wacker et al., 2008), suggesting that DHEA modulates territorial aggression during the non-breeding season in some avian species.

Similarly, in Siberian hamsters, a solitary species in which both males and females are more aggressive during the non-breeding season (Demas et al., 2004; Scotti et al., 2007), SD animals exhibit lower levels of circulating gonadal steroids, but higher levels of circulating DHEA than LD animals (Jasnow et al., 2002; Rendon et al., 2015; Scotti et al., 2007, 2008). Furthermore, SD male and female hamsters show aggression-induced decreases in serum DHEA and/or T, suggesting that these animals may increase the metabolism of circulating DHEA and T to E_2 following an aggressive encounter during the non-breeding season (Munley et al., 2020; Rendon & Demas, 2016; Rendon et al., 2020). In additional studies, we determined that SD females have significantly higher adrenal DHEA content than LD females and that SD, but not LD females show an increase in serum DHEA levels in response to adrenocorticotropic hormone (ACTH) challenge, in which the hypothalamic–pituitary–adrenal axis is stimulated via exogenous administration of ACTH. Notably, the effects of DHEA on non-breeding aggression occur independently of other adrenal hormones (i.e., glucocorticoids, catecholamines); SD males that receive adrenalectomies exhibit reduced levels of aggressive behavior, yet adrenal demodulation, in which the catecholamine-secreting adrenal medulla is removed, produces no change in aggression (Demas et al., 2004). In addition, SD photoperiods do not affect serum or adrenal cortisol content, nor does cortisol treatment affect aggressive behavior in LD or SD males (Scotti et al., 2015). Collectively, these findings indicate that DHEA, but not other adrenal hormones, contributes to increased aggression during the non-breeding season in this species.

Although the research described above supports a role for adrenal DHEA in regulating non-breeding territorial aggression, it is important to note that similar associations between DHEA and aggression are not observed in all vertebrates, particularly in some seasonally breeding songbirds and in non-seasonal rodents. For example, male European starlings exhibit lower plasma DHEA concentrations during the non-breeding season, when aggressive non-courtship and vocalization behavior is displayed, compared with the breeding season (Pintér et al., 2011). Furthermore, DHEA administration does not increase aggressive behavior in male European nuthatches (*Sitta europaea*), a species in which both males and females defend a single territory year-round (Landys et al., 2013; Matthysen, 1998). There is also considerable evidence of an inverse relationship between DHEA and aggression in laboratory mice. Castrated male mice display lower levels of aggression towards lactating female mice when given exogenous DHEA (Haug et al., 1983; Schlegel et al., 1985; Young et al., 1991). Similarly, DHEA reduces aggressive behavior displayed toward intact, ovariectomized, and lactating females when administered to ovariectomized female mice (Bayart et al., 1989; reviewed in Brain & Haug, 1992; Perché et al., 2001). Thus, these data demonstrate that aggressive behavior is regulated independently of DHEA in some non-seasonal and seasonally breeding animals.

2.2.2 | Steroidogenic enzymes

To date, the role of steroidogenic enzymes in modulating seasonal aggression has mainly been studied via pharmacological

manipulations or by quantifying seasonal changes in the expression of steroid-synthesizing and steroid-metabolizing enzymes in the brain. Two steroidogenic enzymes have been the primary focus of neuroendocrine studies of seasonal aggression: 3β-hydroxysteroid dehydrogenase (3β-HSD), an enzyme that catalyzes the conversions of pregnenolone to progesterone and DHEA to androstenedione, and aromatase (ARO), an enzyme that catalyzes the conversion of T to E_2. Male song sparrows exhibit seasonal changes in both 3β-HSD and ARO in the brain. Specifically, non-breeding males exhibit higher 3β-HSD activity in the caudal telencephalon (contains the LS) and ventromedial telencephalon (contains the nucleus taeniae, the avian homolog of the MeA) compared with breeding male sparrows (Pradhan et al., 2010). Moreover, the activity and/or mRNA expression of ARO is higher in diencephalic nuclei (e.g., POA, BNST) in breeding males than in non-breeding males, but is similar in the VMH and ventromedial telencephalon during the breeding and non-breeding seasons (Soma et al., 2003; Wacker et al., 2010). Although additional studies are necessary to determine if seasonal variation in steroidogenic enzymes is related to aggression and whether other seasonally breeding songbirds show similar changes in the activity and expression of steroid-synthesizing and steroid-metabolizing enzymes in the brain, these findings suggest that local changes in neural steroid metabolism could contribute to non-breeding aggression in male song sparrows.

In rodents, seasonal plasticity in steroidogenic enzyme activity appears to be species-specific. In beach mice (*Peromyscus polionotus*), which display higher levels of territorial aggression during the non-breeding season, treatment with the ARO inhibitor fadrozole reduces aggression in SD males, whereas fadrozole administration increases aggression in LD males. E_2 injections, however, prevent the effects of fadrozole on these behavioral phenotypes (Trainor, Lin, et al., 2007). Conversely, there are no differences in the density of ARO-immunoreactive cells in the PAG and two brain regions that regulate reproductive behaviors (the paraventricular nucleus of the hypothalamus and ventral tegmental area) between LD and SD female Siberian hamsters (Rendon et al., 2020). Interestingly, we recently determined that Siberian hamsters exhibit seasonal and sex differences in adrenal and neural 3β-HSD activity, despite males and females showing a similar aggressive phenotype during the non-breeding season. Specifically, SD males show higher 3β-HSD activity in the adrenal glands than LD males, whereas SD females exhibit reductions in 3β-HSD activity in the adrenal glands and AH relative to LD females (K. M. Munley, J. C. Trinidad, & G. E. Demas, unpublished results). Collectively, these data support a role for steroid-synthesizing and steroid-metabolizing enzymes in regulating seasonal aggression and suggest that seasonal plasticity in steroidogenic enzymes may be sex-specific in some rodents.

2.2.3 | Steroid receptors

Thus far, prior research in songbirds suggests that seasonal plasticity in steroid receptors in brain regions associated with aggression varies across species. In male spotted antbirds, ERα mRNA expression in the POA and AR mRNA expression in the nucleus taeniae are higher during the non-breeding season than the breeding season (Canoine et al., 2007). Conversely, breeding male sparrows exhibit higher AR mRNA expression in the POA than non-breeding males, but there are no seasonal differences in ERα and ERβ mRNA expression in brain regions associated with aggressive and/or sexual behavior (Wacker et al., 2010). Similarly, pharmacological inhibition of the androgenic and estrogenic actions of T via the AR antagonist flutamide and the ARO inhibitor 1,4,6-androstatriene-3,17-dione reduces territorial aggression in breeding, but not non-breeding male European stonechats (*Saxicola torquata rubicola*; Canoine & Gwinner, 2002; Marasco et al., 2011). Although the relationship between these seasonal changes in neural steroid receptor expression and aggressive behavior has not yet been investigated, these results suggest that some seasonally breeding songbirds exhibit region-specific variation in neural steroid receptors, but that these changes are species-specific.

Moreover, studies in seasonally breeding rodents have documented differences in the expression and abundance of ERs across the annual cycle and characterized their potential role in regulating aggressive behavior. SD male beach mice and deer mice (*Peromyscus maniculatus*) show increases in ERα abundance and expression in the BNST, but exhibit reductions in ERβ abundance and expression in the BNST and MeA relative to LD males (Trainor, Rowland, et al., 2007). In addition, selective activation of ERα or ERβ is associated with elevated aggression in SD male beach mice, but these increases in aggression are not related to changes in estrogen-dependent gene expression in the BNST or POA (Trainor, Lin, et al., 2007). Similarly, non-breeding aggression is positively associated with ERα abundance in brain regions associated with aggressive behavior in SD male and female Siberian hamsters (i.e., PAG, LS, MeA, and/or BNST), but not in brain regions associated with reproductive behavior (i.e., POA, arcuate nucleus, and the anteroventral periventricular nucleus of the hypothalamus; Kramer et al., 2008; Rendon et al., 2017). Interestingly, there are no differences in ERα and ERβ immunostaining in the LS, POA, BNST, or MeA between seasonal phenotypes of male California mice, a species that displays higher levels of territorial aggression during the non-breeding season, but does not exhibit gonadal regression (Laredo et al., 2013; Nelson et al., 1995; Trainor et al., 2008). Thus, these findings indicate that ERs modulate nonbreeding aggression in rodent species that are reproductively responsive to changes in photoperiod.

2.2.4 | Neurosteroids

In addition to the peripheral secretion of steroid hormones, vertebrates are also capable of synthesizing steroids *de novo* from cholesterol in the brain (reviewed in Do Rego et al., 2009, 2012). The idea of "neurosteroids," or brain-derived steroid hormones, was first introduced to describe the high levels of DHEA and its sulfated form, DHEA-S, that were measured in the rat brain following castration and adrenalectomy (Baulieu, 1981; Corpéchot

et al., 1981). It is now well-established that DHEA, among other steroid hormones (e.g., allopregnenalone), can be synthesized *de novo* within the central nervous system and can act locally on specific neural substrates to regulate social behaviors, including aggression (Jalabert et al., 2018; Simon, 2002). Thus, it is likely that both neurosteroids and neurally-derived androgens and estrogens (i.e., androgens and estrogens derived from circulating steroids) modulate the neural circuits relevant to aggressive behavior in a seasonal manner (reviewed in Munley et al., 2018; Soma et al., 2015).

Historically, few studies have assessed how seasonal plasticity in neurosteroids regulates aggression, primarily due to limitations in hormone assay sensitivity. Over the past decade, however, quantification methods that exhibit greater sensitivity and specificity for steroid hormones have emerged (e.g., liquid chromatography-tandem mass spectrometry; reviewed in Munley et al., 2022; Taves et al., 2011), enabling researchers to investigate how regional changes in steroid levels within the brain can influence social behavior. To date, only three studies have characterized seasonal variation in neurosteroid levels in two seasonally breeding species: song sparrows and Siberian hamsters. Male song sparrows exhibit seasonal variation in neurosteroid concentrations within the SBN; non-breeding males have lower levels of T and E_2 in the POA, AH, and nucleus taeniae, but have higher levels of progesterone in the POA, AH, VMH, and nucleus taeniae than breeding males. There are no differences in the concentrations of neural DHEA or corticosterone, however, between breeding and non-breeding male sparrows (Heimovics et al., 2016; Jalabert et al., 2021). Conversely, SD male Siberian hamsters have lower levels of DHEA, T, and E_2 in the LS, AH, MeA, and/or PAG than LD males, but there are no differences in the concentrations of progesterone or cortisol between LD and SD male hamsters. Interestingly, LD and SD male hamsters also show distinct relationships between neurosteroid levels and aggression; while neural progesterone and DHEA are positively correlated with aggression, regardless of photoperiodic treatment, only SD males exhibit negative correlations between neural T, E_2, and cortisol concentrations and aggressive behavior (Munley et al., 2021). Although further research is needed to determine whether seasonal variation in neurosteroids is exhibited by other seasonally breeding species, these studies provide preliminary evidence that neurosteroids may mediate seasonal changes in aggression in some animals.

3 | PINEAL MELATONIN AND SEASONAL CHANGES IN SOCIAL BEHAVIOR

As described above, biological responses to photoperiod are mediated by changes in the pineal indolamine melatonin in most mammals. Photoperiod is translated from an environmental cue into a biochemical signal via a multisynaptic pathway, in which environmental light is perceived by retinal ganglion cells, processed in the hypothalamus, and transduced from a neural to an endocrine signal through the release of melatonin by the pineal gland. Because melatonin is secreted predominantly during darkness, it is the precise pattern of melatonin secretion, and not the amount of hormone *per se*, that conveys information about day length to the central nervous system and peripheral tissues that are sensitive to melatonin (reviewed in Bartness et al., 1993; Goldman, 2001). This mechanism is supported by field and laboratory studies, which have shown that pinealectomy, which eliminates melatonin secretion and renders animals physiologically "blind" to day length, prevents reproductive inhibition during SDs, whereas treating LD animals with exogenous melatonin that mimics a SD-like pattern of secretion inhibits reproduction (Bittman et al., 1983; B. Goldman et al., 1979; Lincoln et al., 1965; Reiter, 1973).

Following its secretion into circulation, melatonin exerts its effects by binding to one of two subtypes of membrane-bound G protein-coupled receptors: the MT_1 melatonin receptor (also known as the Mel_{1a} receptor in non-mammalian vertebrates and MTNR1A in humans) and the MT_2 melatonin receptor (also known as the Mel_{1b} receptor in non-mammalian vertebrates and MTNR1B in humans; reviewed in Dubocovich & Markowska, 2005; von Gall et al., 2002; Witt-Enderby et al., 2003). Of these subtypes, the MT_1 receptor is considered to be primarily responsible for photoperiodic signal transduction (reviewed in Reppert, 1997), since the MT_1 receptor is expressed in brain regions and endocrine tissues that are important sites for the biological and circadian actions of melatonin (e.g., the suprachiasmatic nucleus [SCN] of the hypothalamus and the pars tuberalis [PT] of the anterior pituitary gland; reviewed in Kennaway & Rowe, 1995; Wood & Loudon, 2014), whereas the MT_2 receptor is largely absent from the hypothalamus and pituitary gland of mammals and is absent entirely from several species of seasonally breeding rodents, including Syrian and Siberian hamsters (reviewed in Reppert, 1997; Weaver et al., 1989, 1996). In addition to the SCN and PT, the MT_1 receptor has been localized in several other brain regions and peripheral endocrine glands, including the hypothalamus (paraventricular nucleus, arcuate nucleus, supraoptic nucleus, ventromedial nucleus, and dorsomedial nucleus; Lacoste et al., 2015; Weaver et al., 1989; Wu et al., 2006), midbrain (dorsal raphe nucleus, superior colliculus, and substantia nigra; Green et al., 2015; Lacoste et al., 2015), thalamus (paraventricular nucleus, nucleus reunions, stria medullaris, and lateral habenula; Adamah-Biassi, Zhang, et al., 2014; Mazzucchelli et al., 1996; Wu et al., 2006), hippocampus (Adamah-Biassi, Zhang, et al., 2014; Lacoste et al., 2015; Mazzucchelli et al., 1996; Musshoff et al., 2002), cerebellum (Adamah-Biassi, Zhang, et al., 2014; Mazzucchelli et al., 1996), gonads (Frungieri et al., 2005; McGuire et al., 2011), and adrenal glands (Richter et al., 2008; Skinner & Robinson, 1995). As with photoperiod, the role of the MT_1 receptor in regulating seasonal changes in physiology and behavior has mostly been studied in the context of reproduction (reviewed in Dawson et al., 2001; Stevenson et al., 2017; Wood & Loudon, 2014). Thus, it is unclear whether MT_1 receptor signaling is also important in modulating seasonal plasticity in non-reproductive social behaviors, such as aggression.

3.1 | Aggressive behavior

Previous work in seasonally breeding rodents has implicated melatonin in modulating territorial aggression (reviewed in Munley et al., 2018; Soma et al., 2015). Pinealectomy prevents SD increases in aggression in female Syrian hamsters, whereas treatment of LD hamsters with exogenous, SD-like melatonin increases aggression. In contrast, ovariectomy and treatment with exogenous E_2, either alone or in combination with progesterone, has no effect on aggression (Badura & Nunez, 1989; Fleming et al., 1988), suggesting that photoperiodic changes in aggression are independent of changes in gonadal steroids in female Syrian hamsters. Similarly, melatonin implants increase social dominance in LD male greater long-tailed hamsters (Wang et al., 2012), and timed melatonin injections, which mimic a SD pattern of endogenous melatonin secretion, increase aggressive behavior in male California mice, male Syrian hamsters, and male and female Siberian hamsters exposed to LD photoperiods (Demas et al., 2004; Jasnow et al., 2002; Laredo et al., 2014; Munley et al., 2020; Rendon et al., 2015, 2020). This behavioral response is partially blocked, however, by the non-selective MT_1/MT_2 receptor antagonist luzindole in male California mice (Laredo et al., 2014). Interestingly, short-term (i.e., 10 days) timed melatonin administration is sufficient to elevate aggressive behavior in LD male Syrian hamsters and female Siberian hamsters, but does not alter gonadal mass or circulating gonadal steroid levels (Jasnow et al., 2002; Rendon et al., 2015). Thus, these studies indicate that photoperiodic changes in aggression are mediated by pineal melatonin, but independent of gonadal steroids, in some rodent species.

Subsequent research has investigated the neuroendocrine mechanisms by which melatonin regulates seasonal plasticity in aggressive behavior. Specifically, our previous work in Siberian hamsters suggests that the actions of melatonin on aggression occur both directly via neural substrates, such as the hypothalamus, pituitary gland, and limbic system, and indirectly via peripheral substrates (e.g., the gonads and adrenal glands; Figure 1; reviewed in Haller et al., 1998; Munley et al., 2018; Soma et al., 2015). There is considerable evidence that DHEA modulates melatonin-induced aggression in this species. LD male and female hamsters given timed melatonin injections (LD-M hamsters) display increased territorial aggression and show SD-like changes in baseline and aggression-induced circulating androgen and estrogen concentrations, including an increase in baseline levels of circulating DHEA (Munley et al., 2020, 2021; Rendon et al., 2015, 2020). This behavioral phenotype, however, is blocked by bilateral adrenalectomy, but is not affected by adrenal demodulation (Demas et al., 2004). Furthermore, treating adrenal glands with melatonin *in vitro* elevates DHEA production in SD, but not LD female hamsters, whereas treating cultured ovaries with melatonin elevates DHEA production in LD, but not SD females (Rendon et al., 2015). Collectively, these findings suggest that melatonin acts via the adrenal glands to increase aggression during the non-breeding season in Siberian hamsters.

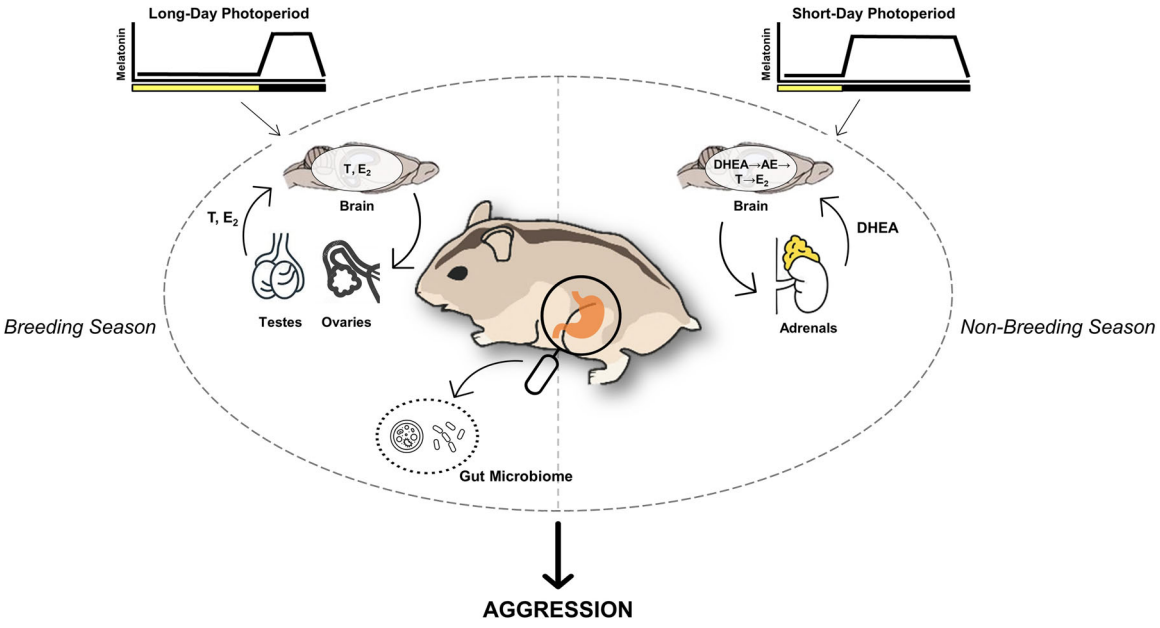

FIGURE 1 Neuroendocrine mechanisms by which melatonin may modulate territorial aggression in seasonally breeding animals. During the long-day photoperiods of the breeding season, animals exhibit a relatively short duration of melatonin secretion. During this time of the year, gonadal steroids (e.g., testosterone [T] and 17β-estradiol [E_2]) can act directly on the neural circuits underlying aggressive behavior. Conversely, animals exhibit a relatively long duration of melatonin secretion during the short-day photoperiods of the non-breeding season. Because many species undergo gonadal regression during the winter months, prohormones, including the adrenal androgen dehydroepiandrosterone (DHEA), are locally converted to more potent androgens (e.g., androstenedione [AE] and T) and estrogens (e.g., E_2) in the brain to regulate aggression. There is emerging evidence that additional mechanisms, such as the gut microbiome, may also influence seasonal aggression

Although few studies have examined how melatonin may act via neural substrates to regulate seasonal aggression, some recent studies suggest that neurosteroids mediate melatonin-dependent increases in non-breeding aggression in Siberian hamsters. LD male hamsters given timed melatonin injections exhibit SD-like reductions in androgens and estrogens in several brain regions associated with aggressive behavior (i.e., the LS, AH, MeA, and PAG). Timed melatonin administration and exposure to SDs also induce similar relationships between neurosteroid concentrations and aggressive behavior (Munley et al., 2021), suggesting that seasonal changes in steroid hormone levels in the brain are regulated, at least in part, by melatonin. In contrast, there is no effect of timed melatonin administration or SDs on the density of ARO immunoreactive neurons in the PAG, paraventricular nucleus of the hypothalamus, and ventral tegmental area in female hamsters (Rendon et al., 2020). There is also emerging evidence that melatonin acts on the brain and adrenal glands in a sex-specific manner; LD-M and SD males have higher 3β-HSD activity in the adrenal glands than LD males, whereas LD-M and SD females have lower 3β-HSD activity in the adrenal glands and AH than LD females (K. M. Munley, J. C. Trinidad, & G. E. Demas, unpublished results). Finally, we recently showed that lentiviral-mediated overexpression of the MT_1 receptor in the adrenal glands causes SD-like changes in social behavior in male Siberian hamsters, including increased aggression. There is no effect of adrenal MT_1 overexpression, however, on serum DHEA levels (Munley et al., 2022), which could suggest that adrenal MT_1 receptors mediate seasonal changes in behavior via signaling mechanisms with neural substrates.

In summary, these studies support the hypothesis that pineal melatonin regulates seasonal plasticity in aggressive behavior via steroid hormones in Siberian hamsters (Figures 1–2). We have shown that a SD-like melatonin signal increases adrenal DHEA secretion and reduces circulating DHEA and T following an aggressive encounter in male and female Siberian hamsters (Figure 2A,B; Munley et al., 2020; Rendon et al., 2020). Moreover, LD-M and SD males show melatonin-dependent decreases in DHEA, T, and E_2 in brain regions associated with aggressive behavior (Figure 2C; Munley et al., 2021). Finally, these melatonin-dependent changes in adrenal and neural steroid levels are associated with an increase in territorial aggression in male and female hamsters (Figure 2D,E; Munley et al., 2021; Rendon et al., 2020). Collectively, these results suggest that melatonin acts in both the periphery and the brain to alter steroid hormone levels and elevate non-breeding aggression in this species. It is important to note that although these studies suggest that circulating melatonin regulates seasonal variation in steroids and aggression in Siberian hamsters, few studies have examined how melatonin may act via the MT_1 melatonin receptor to modulate seasonal changes in aggressive behavior. Moreover, it is unclear whether melatonin regulates aggression via direct or indirect mechanisms (i.e., via the brain or peripheral tissues). Thus, further research is necessary to determine how MT_1 receptors contribute to seasonal aggression and to assess whether the neuroendocrine processes underlying melatonin-induced aggression in Siberian hamsters are evolutionarily conserved in other seasonally breeding species.

3.2 | Non-aggressive social behavior

In addition to seasonal changes in aggression, recent studies suggest that some animals show variation in other social behaviors, including reward and affective behaviors (e.g., anxiety-like and depressive-like behaviors), across the annual cycle. Although traditionally considered to be maladaptive in humans, reward-seeking and anxiety- and depressive-like behaviors may be adaptive in wild animals under certain environmental conditions. As mentioned previously, prioritizing survival over other energetically costly processes (e.g., reproduction) during the non-breeding season is often beneficial to seasonally breeding animals, particularly for species that experience harsh environmental conditions and a relative scarcity of biotic and abiotic resources during the winter months (reviewed in Walton et al., 2011; Wilsterman et al., 2019). Thus, it is logical that symptoms associated with affective disorders and/or altered reward function (e.g., lethargy, altered food intake, loss of motivation, fearfulness) may enable animals to conserve energy during the non-breeding season, a time of the year during which individuals face these energetic bottlenecks (reviewed in Nesse, 2000; Nesse & Williams, 1996; Wehr et al., 2001).

While few studies have investigated seasonal plasticity in affective and reward-seeking behaviors and their neuroendocrine substrates, there is emerging evidence that these behaviors are regulated by melatonin in both seasonally and non-seasonally breeding rodents. These mechanisms have primarily been explored in a laboratory setting using photoperiodic, pharmacological, and molecular genetic approaches. In general, prior studies suggest that exposure to SD photoperiods, which are characterized by a relatively long duration of pineal melatonin secretion, decreases reward-seeking behavior and increases anxiety- and depressive-like behaviors in seasonal and non-seasonal rodent species. LDs reduce depressive-like behaviors in laboratory rats (*Rattus rattus*), including decreased immobility during the forced swim test (FST; Molina-Hernandez & Tellez-Alcantara, 2000), whereas SDs decrease neophobia in BALB/c and C3H/He house mice and increase anxiety-like behavior in laboratory rats, as measured via open field and elevated plus maze tests (OFT and EPM, respectively; Benabid et al., 2008; Kopp et al., 1999). Similar deficits in reward-seeking and affective behaviors have been reported in seasonally breeding rodents; SD male fat sand rats (*Psammomys obesus*) show increased anhedonia and anxiety- and depressive-like behaviors, including reduced saccharin consumption, greater time spent in the closed arm section of the EPM, and increased immobility during the FST, compared to LD males (Ashkenazy et al., 2009; Einat et al., 2006). Juvenile male Siberian hamsters also spend more time in the closed arms of the EPM and show greater immobility during the FST relative to LD males (Prendergast & Nelson, 2005), and male and female hamsters exposed to SDs post-weaning exhibit more anxiety-like and depressive-like behaviors as adults compared with LD animals (Pyter & Nelson, 2006). Similarly, LD collared lemmings (*Dicrostonyx groenlandicus*) display reduced anxiety-like responses during the EPM, whereas lemmings housed in an intermediate photoperiod show lower levels of depressive-like behaviors compared to LD and

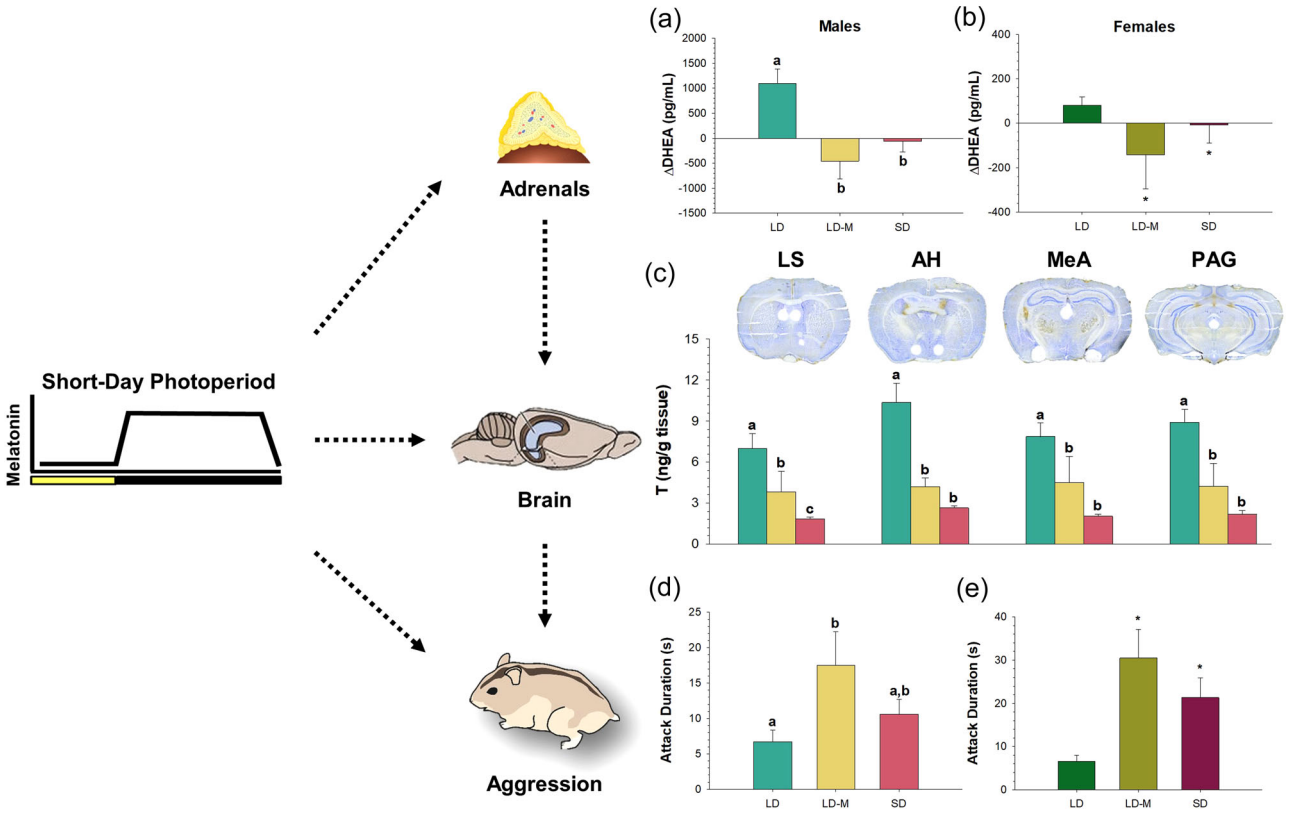

FIGURE 2 Pineal melatonin regulates seasonal aggression in Siberian hamsters via steroid hormones. (a,b) Changes in serum dehydroepiandrosterone (DHEA) levels following an aggressive interaction, (c) neural testosterone (T) concentrations in the lateral septum (LS), anterior hypothalamus (AH), medial amygdala (MeA), and periaqueductal gray (PAG), and (d–e) attack duration of long-day (LD; males: cyan, females: green) male and female Siberian hamsters, LD hamsters given timed melatonin injections (LD-M; males: yellow, females: olive), and hamsters that were exposed to short-day photoperiods (SD; males: pink, females: magenta). Data are presented as mean ± SEM. "*" indicates a significant difference from LD hamsters, and different lowercase letters indicate a significant difference between treatment groups. Data are modified and reprinted with permission from the authors (Munley et al., 2020, 2021; Rendon et al., 2020). (c) Contains data from male Siberian hamsters.

SD lemmings (Weil et al., 2007). Collectively, these results suggest that reward and affective behaviors are influenced by photoperiod in seasonal and non-seasonal rodents.

Additional research has assessed the roles of circulating melatonin and its receptors in regulating reward-seeking and anxiety- and depressive-like behaviors. Male and female MT_1 receptor knockout C57BL/6 and C3H/HeN house mice show higher levels of anxiety- and depressive-like behaviors than wild-type mice, including decreased mobility during the FST and tail suspension test, increased marble burying, and reduced time spent in the center of the OFT (Adamah-Biassi, Hudson, et al., 2014; Comai et al., 2015; Liu, Clough, et al., 2017; Weil et al., 2006). Conversely, MT_2 receptor knockout male C3H/HeN house mice display higher levels of anxiety-like behavior during novelty-suppressed feeding and light/dark box tests, but show no difference in depressive-like behavior relative to wild-type mice (Comai et al., 2020). Interestingly, knockout of either the MT_1 or MT_2 receptor is sufficient to reduce reward-seeking behaviors in C3H/HeN male house mice, including decreased sucrose consumption and an inability to develop conditioned place preference for food- or methamphetamine-induced reinforcement (Clough et al., 2014, 2018; Comai et al., 2015). A role for melatonin in modulating affective and reward behaviors is further supported by pharmacological studies; luzindole administration reduces depressive-like behavior in wild-type male C3H/HeN house mice (Dubocovich et al., 1990), whereas melatonin treatment ameliorates depressive-like behavior in male BALB/c male house mice exposed to chronic mild stress (Vega-Rivera et al., 2020). In contrast, melatonin treatment increases anhedonia, anxiety-like behaviors, and depressive-like behaviors in LD male fat sand rats (Ashkenazy et al., 2009), suggesting that the actions of melatonin on affective and reward behaviors may differ between seasonally and non-seasonally breeding rodents. Future research should characterize the neuroendocrine mechanisms by which melatonin and its receptors modulate these behaviors and investigate how these processes may differ between species that breed seasonally and those that breed year-round.

4 | SEASONAL PLASTICITY IN HUMAN AGONISTIC AND AFFECTIVE BEHAVIORS

While humans have traditionally been considered "aseasonal," at least with respect to reproductive physiology and morphology, some findings suggest that humans, like non-human animals, show seasonal

plasticity in behavioral phenotypes, including social and affective behaviors (Nelson et al., 2010). Perhaps the most well-studied seasonal response in humans is seasonal affective disorder (SAD, i.e., seasonal depression). The recognition of SAD is supported by historical data showing that suicide rates often increase in late spring, depending on the latitudinal region (Altamura et al., 1999; Lee et al., 2006; Rocchi et al., 2007; Rock et al., 2003). Since its identification, SAD has been associated with SD photoperiods and has been treated with bright light phototherapy (Rosenthal, Sack, James, et al., 1985). This treatment appears intuitive—winter photoperiods extend circulating melatonin and contribute to SAD etiology, whereas bright light phototherapy can ameliorate symptoms by suppressing melatonin. In fact, treatment of SAD patients with extended phototherapy suppresses the urinary secretion of the major melatonin metabolite 6-hydroxymelatonin while also decreasing depressive symptoms (Rosenthal, Sack, Carpenter, et al., 1985). Interestingly, however, more recent findings suggest that bright white light (10,000 lux) need only be applied for 1 h during the daytime to alleviate seasonal depression symptoms, and an effect can be observed after a single treatment (Reeves et al., 2012). These data suggest that SAD may also be regulated by changes in neurotransmitter levels (e.g., serotonin, dopamine), in addition to melatonin (reviewed in Gupta et al., 2013; Levitan, 2007; Praschak-Rieder & Willeit, 2012).

Recently, a relationship between seasonality and aggression has also been observed in humans, with aggressive behavior typically being highest during the summer and lowest during the winter (Geoffroy & Amad, 2016; Kuivalainen et al., 2017; Morken & Linaker, 2000; Tiihonen et al., 1997). For example, annual rhythms in violent crimes have been demonstrated that track seasonal variation in photoperiod. Specifically, in the northern hemisphere, violent crimes show strong seasonal patterns, whereas non-violent crimes exhibit no such pattern. Inverse rhythms in aggressive crimes occur in the southern hemisphere (Schreiber et al., 1997). Furthermore, there are spring and winter peaks in the number of affective disorder patients admitted for excessive aggression (Fux et al., 1995). However, some reports indicate a peak in violent acts during the winter (Bader et al., 2014; Koutaniemi & Einiö, 2019), which suggests that other elements of seasonality (e.g., frequency and duration of social interaction) may also play an important role in the frequency of violent behavior in humans. It is important to note that humans are a diurnal species, whereas most rodents are nocturnal; as such, melatonin has different actions on activity levels and, likely, social behaviors. Thus, it is not surprising that differences in social and physiological factors could explain why humans and rodents may exhibit inverse patterns in seasonal aggression (see also Paribello et al., 2022).

Human studies have also provided preliminary support for a potential role of melatonin in mediating seasonal aggression. In a clinical context, bright light inhibits, whereas exogenous melatonin increases aggression in patients suffering from dementia (Haffmans et al., 2001). A recent experimental study also demonstrated that oral melatonin increases reactive aggression in adult males. In this study, participants were given melatonin or placebo 1.5 h before a Taylor aggression paradigm, in which participants compete with high- or low-provoking opponents and choose the severity of punishment administered. In both cases, participants who received melatonin chose higher punishments for their opponents than participants who received placebo (Liu, Zhong, et al., 2017), suggesting that melatonin plays at least a modulatory role in human aggression.

As with seasonal variation in non-human aggression, adrenal DHEA may also play a role in human aggression. For example, prepubertal boys with conduct disorder (defined as a collection of symptoms, including aggression directed towards people or animals) have higher baseline levels of DHEA-S, but not T compared with normal control boys. DHEA-S concentrations are also correlated with the intensity of aggression, as rated by parents and teachers (van Goozen et al., 1998). Furthermore, plasma DHEA-S concentrations are higher in boys with conduct disorder than in boys with attention-deficit/hyperactivity disorder (ADHD) or normal controls (van Goozen et al., 2000). DHEA may play a role in adult aggression as well. In a study of alcohol withdrawal, serum levels of DHEA-S were lower in alcohol-dependent compared to control subjects during late alcohol withdrawal. When alcohol-dependent subjects were separated into high and low aggression groups, lower basal DHEA-S levels were seen during early alcohol withdrawal in high aggression individuals, whereas DHEA was lower during late withdrawal in low aggression individuals relative to control subjects (Ozsoy & Esel, 2008). Collectively, these data suggest an important, albeit complicated, relationship between changes in DHEA and aggression in humans. It is important to note, however, that these studies did not explicitly examine a role for DHEA in aggression in psychologically healthy humans, nor whether these effects are influenced by seasonal changes in melatonin. Thus, future studies are needed to address a potential role for DHEA in mediating seasonal aggression in healthy human populations.

5 | FUTURE DIRECTIONS AND CONCLUSIONS

As discussed above, numerous studies in non-humans, as well as a smaller but growing number of studies in humans, have implicated changes in photoperiod (and thus, circulating melatonin) in mediating seasonal aggression. While emerging evidence implicates seasonal variation in steroid hormones and their metabolism in regulating aggressive behavior, additional physiological mechanisms are likely involved. One such mechanism, the microbiome, has recently become a hot topic within the fields of biology and medicine. The gut microbiome, a microbial community composed of commensal, symbiotic, and pathogenic bacteria, fungi, and viruses that live in the gastrointestinal tract of mammals, is strongly associated with an organism's brain and behavior, including social behaviors (reviewed in Cani, 2018; Cusick et al., 2021; Shreiner et al., 2015). For virtually all animals, including humans, the gut microbiome plays an important role in survival, but its importance has traditionally been under-appreciated (Møller et al., 2009; reviewed in Williams et al., 2020). It is well-established that the brain can affect the structure and function of the intestinal microbial community through the

autonomic nervous and neuroendocrine systems. Thus, there is a robust, bidirectional interaction between the brain and gut microbiome within individuals, which forms the "brain–gut–microbiome axis" (reviewed in Martin et al., 2018).

The brain–gut–microbiome axis likely contributes to seasonal changes in physiology and behavior in human and non-human animals, but to date, few studies have investigated the interactions among these systems in a seasonal context. For example, decreases in melatonin synthesis in the brain contribute to changes in intestinal permeability (reviewed in Anderson & Maes, 2015). Our group has begun to explore the influences of seasonal variation in the gut microbiome on social behaviors, including aggression, in male and female Siberian hamsters (Figure 1). Recently, we demonstrated that male and female hamsters exposed to SDs show significant changes in the relative abundance of gut bacterial phyla and families and that SD females display higher levels of aggression than LD females. Furthermore, the relative abundance of some bacterial families is positively associated with aggressive behavior in SD female hamsters (Ren et al., 2020), suggesting that seasonal changes in aggression may be mediated, at least in part, by photoperiod-dependent effects on the gut microbiome. While an explicit role for melatonin was not examined in this study, recent findings have also demonstrated photoperiodic changes in microbial species richness in the gut microbiome of Siberian hamsters, effects that are partially ameliorated via surgical pinealectomy (Shor et al., 2020). Ongoing studies will determine which gut microbiome families directly impact male and female aggression and will elucidate the role of melatonin in regulating seasonal plasticity in the gut microbiome. In addition, while some research has examined seasonal changes in non-aggressive social and affective behaviors, as well as a potential role for melatonin in mediating changes in these behaviors, much less is known about these mechanisms relative to aggressive behavior. Thus, additional research on seasonal and melatonin-dependent changes in non-aggressive social behaviors (e.g., reward and affective behaviors) and their interaction with other neuroendocrine substrates (e.g., gonadal, adrenal, or neural steroids) is warranted, particularly in seasonally breeding species. Continued studies will be critical for characterizing the neuroendocrine mechanisms by which melatonin modulates seasonal plasticity in social behavior in vertebrates. More broadly, this research will provide insight into how variation in these social behaviors and their underlying physiological processes enhance reproductive success and subsequent fitness across the annual cycle.

ACKNOWLEDGMENTS

We thank current and former members of the Demas lab for their assistance with data collection and for their intellectual contributions to the studies discussed in this review. We are also grateful to Dr. Tyler Stevenson, Dr. Gaurav Majumdar, and Dr. Chris Marshall for the invitation to submit this review. This work was funded in part by National Institutes of Mental Health Grant R21MH109942 (to G. E. D.), National Science Foundation Grant IOS-1656414 (to G. E. D.), National Institute of Child Health and Human Development Training Grant T32HD049336 (to K. M. M. and G. E. D.), an Indiana Academy of Science Senior Research Grant (to K. M. M.), an IU Center for the Integrative Study of Animal Behavior Predoctoral Fellowship (to K. M. M.), an IU College of Arts and Sciences Dissertation Research Fellowship (to K. M. M.), an IU Department of Biology Louise Constable Hoover Fellowship (to K. M. M.), as well as generous research funds from Indiana University.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Kathleen M. Munley http://orcid.org/0000-0002-7409-3508
Gregory E. Demas http://orcid.org/0000-0003-3914-0900

REFERENCES

Adamah-Biassi, E. B., Hudson, R. L., & Dubocovich, M. L. (2014). Genetic deletion of MT_1 melatonin receptors alters spontaneous behavioral rhythms in male and female C57BL/6 mice. *Hormones and Behavior*, *66*(4), 619–627. https://doi.org/10.1016/j.yhbeh.2014.08.012

Adamah-Biassi, E. B., Zhang, Y., Jung, H., Vissapragada, S., Miller, R. J., & Dubocovich, M. L. (2014). Distribution of MT_1 melatonin receptor promoter-driven RFP expression in the brains of BAC C3H/HeN transgenic mice. *Journal of Histochemistry & Cytochemistry*, *62*(1), 70–84. https://doi.org/10.1369/0022155413507453

Adkins, E., & Schlesinger, L. (1979). Androgens and the social behavior of male and female lizards (*Anolis carolinensis*). *Hormones and Behavior*, *13*(2), 139–152. https://doi.org/10.1016/0018-506X(79)90053-9

Albers, H. E., Huhman, K. L., & Meisel, R. L. (2002). Hormonal basis of social conflict and communication. In D. W. Pfaff (Ed.), *Hormones, brain and behavior* (Vol. 1, pp. 393–433). Academic Press.

Altamura, C., VanGastel, A., Pioli, R., Mannu, P., & Maes, M. (1999). Seasonal and circadian rhythms in suicide in Cagliari, Italy. *Journal of Affective Disorders*, *53*(1), 77–85.

Anderson, G., & Maes, M. (2015). The gut–brain axis: The role of melatonin in linking psychiatric, inflammatory and neurodegenerative conditions. *Advances in Integrative Medicine*, *2*(1), 31–37. https://doi.org/10.1016/j.aimed.2014.12.007

Ashkenazy, T., Einat, H., & Kronfeld-Schor, N. (2009). We are in the dark here: Induction of depression- and anxiety-like behaviours in the diurnal fat sand rat, by short daylight or melatonin injections. *International Journal of Neuropsychopharmacology*, *12*(1), 83–93. https://doi.org/10.1017/S1461145708009115

Bader, S., Evans, S. E., & Welsh, E. (2014). Aggression among psychiatric inpatients: The relationship between time, place, victims, and severity ratings. *Journal of the American Psychiatric Nurses Association*, *20*(3), 179–186.

Badura, L. L., & Nunez, A. A. (1989). Photoperiodic modulation of sexual and aggressive behavior in female golden hamsters (*Mesocricetus auratus*): Role of the pineal gland. *Hormones and Behavior*, *23*(1), 27–42. https://doi.org/10.1016/0018-506X(89)90072-X

Baggerman, B. (1966). On the endocrine control of reproductive behaviour in the male three-spined stickleback (*Gasterosteus aculeatus* L.). *Symposia of the Society for Experimental Biology*, *20*, 427–456.

Bartness, T. J., Demas, G. E., & Song, C. K. (2002). Seasonal changes in adiposity: The roles of the photoperiod, melatonin and other hormones, and sympathetic nervous system. *Experimental Biology and Medicine*, *227*(6), 363–376. https://doi.org/10.1177/153537020222700601

Bartness, T. J., Bradley, J., Hastings, M. H., Bittman, E. L., & Goldman, B. D. (1993). The timed infusion paradigm for melatonin delivery: What has it taught us about the melatonin signal, its reception, and the photoperiodic control of seasonal responses? *Journal of Pineal Research*, *15*(4), 161–190. https://doi.org/10.1111/j.1600-079X.1993.tb00903.x

Baulieu, E. E. (1981). Steroid hormones in the brain: Several mechanisms? In K. Fuxe, J. Å. Gustafsson, & L. Wetterberg (Eds.), *Steroid hormone regulation of the brain* (pp. 3–14). Pergamon Press.

Bayart, F., Spetz, J. F., Cittone, L., & Haug, M. (1989). The role of gender and hormonal state on aggression during encounters between resident and intruder mice. *Medical Science Research*, *17*, 517–519.

Beck, S. G., & Handa, R. J. (2004). Dehydroepiandrosterone (DHEA): A misunderstood adrenal hormone and spine-tingling neurosteroid? *Endocrinology*, *145*(3), 43–68. https://doi.org/10.1210/en.2003-1703

Benabid, N., Mesfioui, A., & Ouichou, A. (2008). Effects of photoperiod regimen on emotional behaviour in two tests for anxiolytic activity in Wistar rat. *Brain Research Bulletin*, *75*(1), 53–59. https://doi.org/10.1016/j.brainresbull.2007.07.016

Bittman, E. L., Dempsey, R. J., & Karsch, F. J. (1983). Pineal melatonin secretion drives the reproductive response to daylength in the ewe. *Endocrinology*, *113*(6), 2276–2283. https://doi.org/10.1210/endo-113-6-2276

Brain, P. B., & Haug, M. (1992). Hormonal and neurochemical correlates of various forms of animal "aggression." *Psychoneuroendocrinology*, *17*(6), 537–551. https://doi.org/10.1016/0306-4530(92)90014-X

Brain, P. F. (1979). Annual research reviews, volume 2: Hormones and aggression. Eden Press.

Bronson, F. H., & Heideman, P. D. (1994). Seasonal regulation of reproduction in mammals. In E. Knobil, & J. D. Neill (Eds.), *The physiology of reproduction* (Vol. 2, 2 ed., pp. 541–584). Raven Press.

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

Camazine, B., Garstka, W., Tokarz, R., & Crews, D. (1980). Effects of castration and androgen replacement on male courtship behavior in the red-sided garter snake (*Thamnophis sirtalis parietalis*). *Hormones and Behavior*, *14*(4), 358–372. https://doi.org/10.1016/0018-506X(80)90025-2

Cani, P. D. (2018). Human gut microbiome: Hopes, threats and promises. *Gut*, *67*(9), 1716–1725. https://doi.org/10.1136/gutjnl-2018-316723

Canoine, V., & Gwinner, E. (2002). Seasonal differences in the hormonal control of territorial aggression in free-living European stonechats. *Hormones and Behavior*, *41*(1), 1–8. https://doi.org/10.1006/hbeh.2001.1720

Canoine, V., Fusani, L., Schlinger, B. A., & Hau, M. (2007). Low sex steroids, high steroid receptors: Increasing the sensitivity of the nonreproductive brain. *Journal of Neurobiology*, *67*(1), 57–67. https://doi.org/10.1002/dneu.20296

Cavigelli, S. A., & Pereira, M. E. (2000). Mating season aggression and fecal testosterone levels in male ring-tailed lemurs (*Lemur catta*). *Hormones and Behavior*, *37*(3), 246–255. https://doi.org/10.1006/hbeh.2000.1585

Clough, S. J., Hudson, R. L., & Dubocovich, M. L. (2018). Food-induced reinforcement is abrogated by the genetic deletion of the MT_1 or MT_2 melatonin receptor in C3H/HeN mice. *Behavioural Brain Research*, *343*, 28–35. https://doi.org/10.1016/j.bbr.2018.01.027

Clough, S. J., Hutchinson, A. J., Hudson, R. L., & Dubocovich, M. L. (2014). Genetic deletion of the MT_1 or MT_2 melatonin receptors abrogates methamphetamine-induced reward in C3H/HeN mice. *Physiology & Behavior*, *132*(10), 79–86. https://doi.org/10.1016/j.physbeh.2014.04.049

Comai, S., Ochoa-Sanchez, R., Dominguez-Lopez, S., Bambico, F. R., & Gobbi, G. (2015). Melancholic-like behaviors and circadian neurobiological abnormalities in melatonin MT_1 receptor knockout mice. *International Journal of Neuropsychopharmacology*, *18*(3), pyu075. https://doi.org/10.1093/ijnp/pyu075

Comai, S., De Gregorio, D., Posa, L., Ochoa-Sanchez, R., Bedini, A., & Gobbi, G. (2020). Dysfunction of serotonergic activity and emotional responses across the light-dark cycle in mice lacking melatonin MT_2 receptors. *Journal of Pineal Research*, *61*(1), e12653.

Corpéchot, C., Robel, P., Axelson, M., Sjövall, J., & Baulieu, E. E. (1981). Characterization and measurement of dehydroepiandrosterone sulfate in rat brain. *Proceedings of the National Academy of Sciences of the United States of America*, *78*(8), 4704–4707. https://doi.org/10.1073/pnas.78.8.4704

Crews, D. (2003). The development of phenotypic plasticity: Where biology and psychology meet. *Developmental Psychobiology*, *43*(1), 1–10. https://doi.org/10.1002/dev.10115

Cunningham, R. L., Lumia, A. R., & McGinnis, M. Y. (2012). Androgen receptors, sex behavior, and aggression. *Neuroendocrinology*, *96*(2), 131–140. https://doi.org/10.1159/000337663

Cusick, J. A., Wellman, C. L., & Demas, G. E. (2021). The call of the wild: Using non-model systems to investigate microbiome–behaviour relationships. *Journal of Experimental Biology*, *224*(10), jeb224485. https://doi.org/10.1242/jeb.224485

Davis, D. E. (1957). Aggressive behavior in castrated starlings. *Science*, *126*(3267), 253. https://doi.org/10.1126/science.126.3267.253

Dawson, A., King, V. M., Bentley, G. E., & Ball, G. F. (2001). Photoperiodic control of seasonality in birds. *Journal of Biological Rhythms*, *16*(4), 365–380. https://doi.org/10.1177/074873001129002079

Demas, G. E., Moffatt, C. A., Drazen, D. L., & Nelson, R. J. (1999). Castration does not inhibit aggressive behavior in adult male prairie voles (*Microtus ochrogaster*). *Physiology & Behavior*, *66*(1), 59–62. https://doi.org/10.1016/s0031-9384(98)00268-6

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

Do Rego, J. L., Seong, J. Y., Burel, D., Leprince, J., Luu-The, V., Tsutsui, K., Tonon, M. C., Pelletier, G., & Vaudry, H. (2009). Neurosteroid biosynthesis: Enzymatic pathways and neuroendocrine regulation by neurotransmitters and neuropeptides. *Frontiers in Neuroendocrinology*, *30*(3), 259–301. https://doi.org/10.1016/j.yfrne.2009.05.006

Do Rego, J. L., Seong, J. Y., Burel, D., Leprince, J., Vaudry, D., Luu-The, V., Tonon, M. C., Tsutsui, K., Pelletier, G., & Vaudry, H. (2012). Regulation of neurosteroid biosynthesis by neurotransmitters and neuropeptides. *Frontiers in Endocrinology*, *3*, 4. https://doi.org/10.3389/fendo.2012.00004

Dubocovich, M. L., & Markowska, M. (2005). Functional MT_1 and MT_2 melatonin receptors in mammals. *Endocrine*, *27*(2), 101–110. https://doi.org/10.1385/ENDO:27:2:101

Dubocovich, M. L., Mogilnicka, E., & Areso, P. M. (1990). Antidepressant-like activity of the melatonin receptor antagonist, luzindole (N-0774), in the mouse behavioral despair test. *European Journal of Pharmacology*, *182*(2), 313–325. https://doi.org/10.1016/0014-2999(90)90290-M

Edwards, D. A. (1969). Early androgen stimulation and aggressive behavior in male and female mice. *Physiology & Behavior*, *4*(3), 333–338. https://doi.org/10.1016/0031-9384(69)90185-1

Edwards, D. A. (1970). Post-neonatal androgenization and adult aggressive behavior in female mice. *Physiology & Behavior*, *5*(4), 465–467. https://doi.org/10.1016/0031-9384(70)90252-0

Einat, H., Kronfeld-Schor, N., & Eilam, D. (2006). Sand rats see the light: Short photoperiod induces a depression-like response in a diurnal rodent. *Behavioural Brain Research*, *173*(1), 153–157. https://doi.org/10.1016/j.bbr.2006.06.006

Epple, G. (1978). Lack of effects of castration on scent marking, displays, and aggression in a South American primate (*Saguinus fuscicollis*). *Hormones and Behavior*, *11*(2), 139–150. https://doi.org/10.1016/0018-506x(78)90043-0

Fleming, A. S., Phillips, A., Rydall, A., & Levesque, L. (1988). Effects of photoperiod, the pineal gland and the gonads on agonistic behavior in female golden hamsters (*Mesocricetus auratus*). *Physiology & Behavior*, *44*(2), 227–234. https://doi.org/10.1016/0031-9384(88)90143-6

Frungieri, M. B., Mayerhofer, A., Zitta, K., Pignataro, O. P., Calandra, R. S., & Gonzalez-Calvar, S. I. (2005). Direct effect of melatonin on Syrian hamster testes: Melatonin subtype 1a receptors inhibition of androgen production, and interaction with the local corticotropin-releasing hormone system. *Endocrinology*, *146*(3), 1541–1552. https://doi.org/10.1210/en.2004-0990

Fux, M., Weiss, M., & Elhadad, D. (1995). Aggressive behaviour as a cause of psychiatric admission: A comparison between schizophrenic and affective disorder patients. *Medicine & Law*, *14*(3-4), 293–300.

Garrett, J. W., & Campbell, C. S. (1980). Changes in social behavior of the male golden hamster accompanying photoperiodic changes in reproduction. *Hormones and Behavior*, *14*(4), 303–319. https://doi.org/10.1016/0018-506X(80)90020-3

Geoffroy, P. A., & Amad, A. (2016). Seasonal influence on mass shootings. *American Journal of Public Health*, *106*(5), e15–e16. https://doi.org/10.2105/AJPH.2016.303065

Goldman, B., Hall, V., Hollister, C., Roychoudhury, P., Tamarkin, L., & Westrom, W. (1979). Effects of melatonin on the reproductive system in intact and pinealectomized male hamsters maintained under various photoperiods. *Endocrinology*, *104*(1), 82–88. https://doi.org/10.1210/endo-104-1-82

Goldman, B. D. (2001). Mammalian photoperiodic system: Formal properties and neuroendocrine mechanisms of photoperiodic time measurement. *Journal of Biological Rhythms*, *16*(4), 283–301. https://doi.org/10.1177/074873001129001980

Goodson, J. L. (2005). The vertebrate social behavior network: Evolutionary themes and variations. *Hormones and Behavior*, *48*(1), 11–22. https://doi.org/10.1016/j.yhbeh.2005.02.003

Gorman, M. R., & Zucker, I. (1995). Testicular regression and recrudescence without subsequent photorefractoriness in Siberian hamsters. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, *269*(4), R800–R806. https://doi.org/10.1152/ajpregu.1995.269.4.R800

Gottreich, A., Zuri, I., Hammel, I., & Terkel, J. (2001). Non-involvement of testosterone in aggressive defense behavior in the male blind mole rat *Spalax ehrenbergi*. *Aggressive Behavior*, *27*(1), 64–72. https://doi.org/10.1002/1098-2337(20010101/31)27:13.0.co;2-c

Green, N. H., Jackson, C. R., Iwamoto, H., Tackenberg, M. C., & McMahon, D. G. (2015). Photoperiod programs dorsal raphe serotonergic neurons and affective behaviors. *Current Biology*, *25*(10), 1389–1394. https://doi.org/10.1016/j.cub.2015.03.050

Gupta, A., Sharma, P. K., Garg, V. K., Singh, A. K., & Mondal, S. C. (2013). Role of serotonin in seasonal affective disorder. *European Review for Medical and Pharmacological Sciences*, *17*(1), 49–55.

Haffmans, P. M., Sival, R. C., Lucius, S. A., Cats, Q., & van Gelder, L. (2001). Bright light therapy and melatonin in motor restless behaviour in dementia: A placebo-controlled study. *International Journal of Geriatric Psychiatry*, *16*(1), 106–110. https://doi.org/10.1002/1099-1166(200101)16:1<106::aid-gps288>3.0.co;2-9

Haller, J., Makara, G. B., & Kruk, M. R. (1998). Catecholaminergic involvement in the control of aggression: Hormones, the peripheral sympathetic, and central noradrenergic systems. *Neuroscience & Biobehavioral Reviews*, *22*(1), 85–97. https://doi.org/10.1016/S0149-7634(97)00023-7

Harding, C. F., Walters, M. J., Collado, D., & Sheridan, K. (1988). Hormonal specificity and activation of social behavior in male red-winged blackbirds. *Hormones and Behavior*, *22*(3), 402–418. https://doi.org/10.1016/0018-506X(88)90011-6

Hau, M., & Beebe, K. (2011). Plastic endocrine regulation of year-round territorial aggression in tropical male spotted antbirds. *General and Comparative Endocrinology*, *172*(2), 305–313. https://doi.org/10.1016/j.ygcen.2011.03.016

Hau, M., Stoddard, S. T., & Soma, K. K. (2004). Territorial aggression and hormones during the non-breeding season in a tropical bird. *Hormones and Behavior*, *45*(1), 40–49. https://doi.org/10.1016/j.yhbeh.2003.08.002

Haug, M., Brain, P. F., & Kamis, A. B. (1986). A brief review comparing the effects of sex steorids on two forms of aggression in laboratory mice. *Neuroscience & Biobehavioral Reviews*, *10*(4), 463–468. https://doi.org/10.1016/0149-7634(86)90007-2

Haug, M., Spetz, J. F., Schlegel, M. L., & Robel, P. (1983). Dehydroepiandrosterone inhibits aggressive behavior in castrated male mice. *Comptes Rendus de l'Académie des Sciences—Series III*, *296*(20), 975–977.

Heimovics, S. A., Prior, N. H., Ma, C., & Soma, K. K. (2016). Rapid effects of an aggressive interaction on dehydroepiandrosterone, testosterone and oestradiol levels in the male song sparrow brain: A seasonal comparison. *Journal of Neuroendocrinology*, *28*(2), 12345. https://doi.org/10.1111/jne.12345

Hiadlovská, Z., Mikula, O., Macholán, M., Hamplová, P., Vošlajerová Bímová, B., & Daniszová, K. (2015). Shaking the myth: Body mass, aggression, steroid hormones, and social dominance in wild house mouse. *General and Comparative Endocrinology*, *223*, 16–26. https://doi.org/10.1016/j.ygcen.2015.09.033

Hume, J. M., & Wynne-Edwards, K. E. (2005). Castration reduces male testosterone, estradiol, and territorial aggression, but not paternal behavior in biparental dwarf hamsters (*Phodopus campbelli*). *Hormones and Behavior*, *48*(3), 303–310. https://doi.org/10.1016/j.yhbeh.2005.04.001

Jalabert, C., Ma, C., & Soma, K. K. (2021). Profiling of systemic and brain steroids in male songbirds: Seasonal changes in neurosteroids. *Journal of Neuroendocrinology*, *33*(1), e12922. https://doi.org/10.1111/jne.12922

Jalabert, C., Munley, K. M., Demas, G. E., & Soma, K. K. (2018). Aggressive behavior. In M. K. Skinner (Ed.), *Encyclopedia of reproduction* (Vol. 1, 2 ed., pp. 242–247). Academic Press: Elsevier.

Jasnow, A. M., Huhman, K. L., Bartness, T. J., & Demas, G. E. (2000). Short-day increases in aggression are inversely related to circulating testosterone concentrations in male Siberian hamsters (*Phodopus sungorus*). *Hormones and Behavior*, *38*(2), 102–110. https://doi.org/10.1006/hbeh.2000.1604

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

Kennaway, D. J., & Rowe, S. A. (1995). Melatonin binding sites and their role in seasonal reproduction. *Journal of Reproduction and Fertility. Supplement*, *49*, 423–435.

Kopp, C., Vogel, E., Rettori, M. C., Delagrange, P., Renard, P., Lesieur, D., & Misslin, R. (1999). Regulation of emotional behaviour by day length in mice: Implication of melatonin. *Behavioural Pharmacology*, *10*(8), 747–752. https://doi.org/10.1097/00008877-199912000-00006

Koutaniemi, E. M., & Einiö, E. (2019). Seasonal variation in seeking help for domestic violence based on Google search data and Finnish police

calls in 2017. *Scandinavian Journal of Public Health*, *49*(3), 254–259. https://doi.org/10.1177/1403494819834098

Kramer, K. M., Simmons, J. L., & Freeman, D. A. (2008). Photoperiod alters central distribution of estrogen receptor α in brain regions that regulate aggression. *Hormones and Behavior*, *53*(2), 358–365. https://doi.org/10.1016/j.yhbeh.2007.11.002

Kuivalainen, S., Vehviläinen-Julkunen, K., Louheranta, O., Putkonen, A., Repo-Tiihonen, E., & Tiihonen, J. (2017). Seasonal variation of hospital violence, seclusion and restraint in a forensic psychiatric hospital. *International Journal of Law and Psychiatry*, *52*, 1–6. https://doi.org/10.1016/j.ijlp.2017.05.004

Labrie, F., Luu-The, V., Bélanger, A., Lin, S. X., Simard, J., Pelletier, G., & Labrie, C. (2005). Is dehydroepiandrosterone a hormone? *Journal of Endocrinology*, *187*(2), 169–196. https://doi.org/10.1677/joe.1.06264

Lacoste, B., Angeloni, D., Dominguez-Lopez, S., Calderoni, S., Mauro, A., Fraschini, F., Descarries, L., & Gobbi, G. (2015). Anatomical and cellular localization of melatonin MT1 and MT2 receptors in the adult rat brain. *Journal of Pineal Research*, *58*(4), 397–417. https://doi.org/10.1111/jpi.12224

Landys, M. M., Goymann, W., Soma, K. K., & Slagsvold, T. (2013). Year-round territorial aggression is independent of plasma DHEA in the European nuthatch *Sitta europaea*. *Hormones and Behavior*, *63*(1), 166–172. https://doi.org/10.1016/j.yhbeh.2012.10.002

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

Laredo, S. A., Villalon Landeros, R., Dooley, J. C., Steinman, M. Q., Orr, V., Silva, A. L., Crean, K. K., Robles, C. F., & Trainor, B. C. (2013). Nongenomic effects of estradiol on aggression under short day photoperiods. *Hormones and Behavior*, *64*(3), 557–565. https://doi.org/10.1016/j.yhbeh.2013.06.002

Lee, H.-C., Lin, H.-C., Tsai, S.-Y., Li, C.-Y., Chen, C.-C., & Huang, C.-C. (2006). Suicide rates and the association with climate: A population-based study. *Journal of Affective Disorders*, *92*(2-3), 221–226. https://doi.org/10.1016/j.jad.2006.01.026

Levitan, R. D. (2007). The chronobiology and neurobiology of winter seasonal affective disorder. *Dialogues in Clinical Neuroscience*, *9*(3), 315–324. https://doi.org/10.31887/DCNS.2007.9.3/rlevitan

Lincoln, G. A., Libre, E. A., & Merriam, G. R. (1965). Long-term reproductive cycles in rams after pinealectomy or superior cervical ganglionectomy. *Journal of Reproduction and Fertility*, *85*(2), 687–704.

Liu, J., Clough, S. J., & Dubocovich, M. L. (2017). Role of the MT_1 and MT_2 melatonin receptors in mediating depressive- and anxiety-like behaviors in C3H/HeN mice. *Genes, Brain and Behavior*, *16*(5), 546–553. https://doi.org/10.1111/gbb.12369

Liu, J., Zhong, R., Xiong, W., Liu, H., Eisenegger, C., & Zhou, X. (2017). Melatonin increases reactive aggression in humans. *Psychopharmacology*, *234*(19), 2971–2978. https://doi.org/10.1007/s00213-017-4693-7

Marasco, V., Fusani, L., Dessì-Fulgheri, F., & Canoine, V. (2011). Non-migratory stonechats show seasonal changes in the hormonal regulation of non-seasonal territorial aggression. *Hormones and Behavior*, *60*(4), 414–419. https://doi.org/10.1016/j.yhbeh.2011.07.010

Martin, C. R., Osadchiy, V., Kalani, A., & Mayer, E. A. (2018). The brain-gut-microbiome axis. *Cellular and Molecular Gastroenterology and Hepatology*, *6*(2), 133–148. https://doi.org/10.1016/j.jcmgh.2018.04.003

Matthysen, E. (1998). *The Nuthatches* (1 ed.). T. & A. D. Poyser.

Mazzucchelli, C., Pannacci, M., Nonno, R., Lucini, V., Fraschini, F., & Stankov, B. M. (1996). The melatonin receptor in the human brain: Cloning experiments and distribution studies. *Molecular Brain Research*, *39*(1-2), 117–126. https://doi.org/10.1016/0169-328X(96)00017-4

McGuire, N. L., Kangas, K., & Bentley, G. E. (2011). Effects of melatonin on peripheral reproductive function: Regulation of testicular GnIH and testosterone. *Endocrinology*, *152*(9), 3461–3470. https://doi.org/10.1210/en.2011-1053

Molina-Hernandez, M., & Tellez-Alcantara, P. (2000). Long photoperiod regimen may produce antidepressant actions in the male rat. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *24*(1), 105–116. https://doi.org/10.1016/S0278-5846(99)00084-6

Møller, A. P., Czirjak, G. Á., & Heeb, P. (2009). Feather micro-organisms and uropygial antimicrobial defences in a colonial passerine bird. *Functional Ecology*, *23*(6), 1097–1102. https://doi.org/10.1111/j.1365-2435.2009.01594.x

Moore, M. C. (1988). Testosterone control of territorial behavior: Tonic-release implants fully restore seasonal and short-term aggressive responses in free-living castrated lizards. *General and Comparative Endocrinology*, *70*(3), 450–459. https://doi.org/10.1016/0016-6480(88)90121-9

Morken, G., & Linaker, O. M. (2000). Seasonal variation of violence in Norway. *American Journal of Psychiatry*, *157*(10), 1674–1678. https://doi.org/10.1176/appi.ajp.157.10.1674

Moyer, K. E. (1971). *The physiology of hostility*. Markham Publishing Company.

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*, 136. https://doi.org/10.3389/fendo.2018.00136

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., Dutta, S., Jasnow, A. M., & Demas, G. E. (2022). Adrenal MT_1 melatonin receptor expression is linked with seasonal variation in social behavior in male Siberian hamsters. *Hormones and Behavior*, *138*, 105099. https://doi.org/10.1016/j.yhbeh.2021.105099

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

Munley, K. M., Wade, K. L., & Pradhan, D. S. (2022). Uncovering the seasonal brain: Liquid chromatography-tandem mass spectrometry (LC-MS/MS) as a biochemical approach for studying seasonal social behaviors. *Hormones and Behavior*, *142*, 105161. https://doi.org/10.1016/j.yhbeh.2022.105161

Musshoff, U., Riewenherm, D., Berger, E., Fauteck, J.-D., & Speckmann, E.-J. (2002). Melatonin receptors in rat hippocampus: Molecular and functional investigations. *Hippocampus*, *12*(2), 165–173. https://doi.org/10.1002/hipo.1105

Nelson, R. J. (2006). *Biology of aggression*. Oxford University Press.

Nelson, R. J., Gubernick, D. J., & Blom, J. M. (1995). Influence of photoperiod, green food, and water availability on reproduction in male California mice (*Peromyscus californicus*). *Physiology & Behavior*, *57*(6), 1175–1180. https://doi.org/10.1016/0031-9384(94)00380-N

Nelson, R. J., Denlinger, D. L., & Somers, D. E. (2010). *Photoperiodism: The biological calendar*. Oxford University Press.

Nelson, R. J., Demas, G. E., Klein, S. L., & Kriegsfeld, L. J. (2002). *Seasonal patterns of stress, immune function, and disease*. Cambridge University Press.

Nesse, R. M. (2000). Is depression an adaptation? *Archives of General Psychiatry*, *57*(1), 14–20. https://doi.org/10.1001/archpsyc.57.1.14

Nesse, R. M., & Williams, G. C. (1996). *Why we get sick: The new science of Darwinian medicine* (1 ed.). Vintage.

Newman, A. E., & Soma, K. K. (2009). Corticosterone and dehydroepiandrosterone in songbird plasma and brain: Effects of season and acute stress. *European Journal of Neuroscience*, *29*(9), 1905–1914. https://doi.org/10.1111/j.1460-9568.2009.06748.x

Newman, S. W. (1999). The medial extended amygdala in male reproductive behavior: A node in the mammalian social behavior network. *Annals of the New York Academy of Sciences*, *877*(1), 242–257. https://doi.org/10.1111/j.1749-6632.1999.tb09271.x

Nicholls, T. J., Goldsmith, A. R., & Dawson, A. (1988). Photorefractoriness in birds and comparison with mammals. *Physiological Reviews*, *68*(1), 133–176. https://doi.org/10.1152/physrev.1988.68.1.133

Norris, D., & Carr, J. (2020). *Vertebrate endocrinology* (6 ed.). Academic Press.

O'Connell, L. A., & Hofmann, H. A. (2011). The vertebrate mesolimbic reward system and social behavior network: A comparative synthesis. *Journal of Comparative Neurology*, *519*(18), 3599–3639. https://doi.org/10.1002/cne.22735

Ozsoy, S., & Esel, E. (2008). Hypothalamic-pituitary-adrenal axis activity, dehydroepiandrosterone sulphate and their relationships with aggression in early and late alcohol withdrawal. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *32*(2), 340–347. https://doi.org/10.1016/j.pnpbp.2007.08.034

Paribello, P., Manchia, M., Bosia, M., Pinna, F., Carpiniello, B., & Comai, S. (2022). Melatonin and aggressive behavior: A systematic review of the literature on preclinical and clinical evidence. *Journal of Pineal Research*, e12794. https://doi.org/10.1111/jpi.12794

Perché, F., Young, J., Robel, P., Simon, N. G., & Haug, M. (2001). Prenatal testosterone treatment potentiates the aggression-inhibiting effect of the neurosteroid dehydroepiandrosterone in female mice. *Aggressive Behavior*, *27*(2), 130–138. https://doi.org/10.1002/ab.5

Pintér, O., Péczely, P., Zsebok, S., & Zelena, D. (2011). Seasonal changes in courtship behavior, plasma androgen levels and in hypothalamic aromatase immunoreactivity in male free-living European starlings (*Sturnus vulgaris*). *General and Comparative Endocrinology*, *172*(1), 151–157. https://doi.org/10.1016/j.ygcen.2011.02.002

Pradhan, D. S., Newman, A. E. M., Wacker, D. W., Wingfield, J. C., Schlinger, B. A., & Soma, K. K. (2010). Aggressive interactions rapidly increase androgen synthesis in the brain during the non-breeding season. *Hormones and Behavior*, *57*(4-5), 381–389. https://doi.org/10.1016/j.yhbeh.2010.01.008

Praschak-Rieder, N., & Willeit, M. (2012). Imaging of seasonal affective disordder and seasonality effects on serotonin and dopamine function in the human brain. In C. Carter, & J. Dalley (Eds.), *Brain imaging in behavioral neuroscience* (Vol. 11). Springer.

Prendergast, B. J., & Nelson, R. J. (2005). Affective responses to changes in day length in Siberian hamsters (*Phodopus sungorus*). *Psychoneuroendocrinology*, *30*(5), 438–452. https://doi.org/10.1016/j.psyneuen.2004.08.008

Prough, R. A., Clark, B. J., & Klinge, C. M. (2016). Novel mechanisms for DHEA action. *Journal of Molecular Endocrinology*, *56*(3), R139–R155. https://doi.org/10.1530/JME-16-0013

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

Quiring, D. P. (1944). Transplantation of testes (by A. A. Berthold). *Bulletin of the History of Medicine*, *16*, 399–401.

Reeves, G. M., Nijjar, G. V., Langenberg, P., Johnson, M. A., Khabazghazvini, B., Sleemi, A., Vaswani, D., Lapidus, M., Manalai, P., Tariq, M., Acharya, M., Cabassa, J., Snitker, S., & Postolache, T. T. (2012). Improvement in depression scores after 1 hour of light therapy treatment in patients with seasonal affective disorder. *The Journal of Nervous and Mental Disease*, *200*(1), 51–55. https://doi.org/10.1097/NMD.0b013e31823e56ca

Reiter, R. J. (1973). Pineal control of a seasonal reproductive rhythm in male golden hamsters exposed to natural daylight and temperature. *Endocrinology*, *92*(2), 423–430. https://doi.org/10.1210/endo-92-2-423

Ren, C. C., Sylvia, K. E., Munley, K. M., Deyoe, J. E., Henderson, S. G., Vu, M. P., & Demas, G. E. (2020). Photoperiod modulates the gut microbiome and aggressive behavior in Siberian hamsters. *Journal of Experimental Biology*, *223*(3), jeb212548. https://doi.org/10.1242/jeb.212548

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., Rudolph, L. M., Sengelaub, D. R., & Demas, G. E. (2015). The agonistic adrenal: Melatonin elicits female aggression via regulation of adrenal androgens. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *282*(1819). https://doi.org/10.1098/rspb.2015.2080

Rendon, N. M., Amez, A. C., Proffitt, M. R., Bauserman, E. R., & Demas, G. E. (2017). Aggressive behaviours track transitions in seasonal phenotypes of female Siberian hamsters. *Functional Ecology*, *31*(5), 1071–1081. https://doi.org/10.1111/1365-2435.12816

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.

Reppert, S. M. (1997). Melatonin receptors: Molecular biology of a new family of G protein-coupled receptors. *Journal of Biological Rhythms*, *12*(6), 528–531. https://doi.org/10.1177/074873049701200606

Richter, H. G., Torres-Farfan, C., Garcia-Sesnich, J., Abarzua-Catalan, L., Henriquez, M. G., Alvarez-Felmer, M., Gaete, F., Rehren, G. E., & Seron-Ferre, M. (2008). Rhythmic expression of functional MT1 melatonin receptors in the rat adrenal gland. *Endocrinology*, *149*(3), 995–1003. https://doi.org/10.1210/en.2007-1009

Rocchi, M. B. L., Sisti, D., Cascio, M. T., & Preti, A. (2007). Seasonality and suicide in Italy: Amplitude is positively related to suicide rates. *Journal of Affective Disorders*, *100*(1-3), 129–136. https://doi.org/10.1016/j.jad.2006.10.003

Rock, D., Greenberg, D. M., & Hallmayer, J. F. (2003). Increasing seasonality of suicide in Australia 1970-1999. *Psychiatry Research*, *120*(1), 43–51. https://doi.org/10.1016/s0165-1781(03)00165-3

Rosenthal, N. E., Sack, D. A., Carpenter, C. J., Parry, B. L., Mendelson, W. B., & Wehr, T. A. (1985). Antidepressant effects of light in seasonal affective disorder. *American Journal of Psychiatry*, *142*(2), 163–170. https://doi.org/10.1176/ajp.142.2.163

Rosenthal, N. E., Sack, D. A., James, S. P., Parry, B. L., Mendelson, W. B., Tamarkin, L., & Wehr, T. A. (1985). Seasonal affective disorder and phototherapy. *Annals of the New York Academy of Sciences*, *453*(1), 260–269. https://doi.org/10.1111/j.1749-6632.1985.tb11816.x

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

Schlegel, M. L., Spetz, J. F., Robel, P., & Haug, M. (1985). Studies on the effects of dehydroepiandrosterone and its metabolites on attack by castrated mice on lactating intruders. *Physiology & Behavior*, *34*(6), 867–870. https://doi.org/10.1016/0031-9384(85)90005-8

Schreiber, G., Avissar, S., Tzahor, Z., Barak-Glantz, I., & Grisaru, N. (1997). Photoperiodicity and annual rhythms of wars and violent crimes. *Medical Hypotheses*, *48*(1), 89–96. https://doi.org/10.1016/s0306-9877(97)90029-3

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

Scotti, M. A., Place, N. J., & Demas, G. E. (2007). Short-day increases in aggression are independent of circulating gonadal steroids in female Siberian hamsters (*Phodopus sungorus*). *Hormones and Behavior*, *52*(2), 183–190. https://doi.org/10.1016/j.yhbeh.2007.03.029

Scotti, M. A., Belén, J., Jackson, J. E., & Demas, G. E. (2008). The role of androgens in the mediation of seasonal territorial aggression in male Siberian hamsters (*Phodopus sungorus*). *Physiology & Behavior*, *95*(5), 633–640. https://doi.org/10.1016/j.physbeh.2008.09.009

Scotti, M. A., 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 and Integrative Physiology*, *323*(5), 331–341. https://doi.org/10.1002/jez.1922

Shor, E. K., Brown, S. P., & Freeman, D. A. (2020). A novel role for the pineal gland: Regulating seasonal shifts in the gut microbiota of Siberian hamsters. *Journal of Pineal Research*, *69*(4), e12696. https://doi.org/10.1111/jpi.12696

Shreiner, A. B., Kao, J. Y., & Young, V. B. (2015). The gut microbiome in health and in disease. *Current Opinion in Gastroenterology*, *31*(1), 69–75. https://doi.org/10.1097/MOG.0000000000000139

Simon, N. G. (2002). Hormonal processes in 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* (pp. 339–392). Academic Press.

Skinner, D. C., & Robinson, J. E. (1995). Melatonin-binding sites in the gonadotroph-enriched zona tuberalis of ewes. *Journal of Reproductive Fertility*, *104*(2), 243–250. https://doi.org/10.1530/jrf.0.1040243

Soma, K. K., & Wingfield, J. C. (2001). Dehydroepiandrosterone in songbird plasma: Seasonal regulation and relationship to territorial aggression. *General and Comparative Endocrinology*, *123*(2), 144–155. https://doi.org/10.1006/gcen.2001.7657

Soma, K. K., Wissman, A. M., Brenowitz, E. A., & Wingfield, J. C. (2002). Dehydroepiandrosterone (DHEA) increases territorial song and the size of an associated brain region in a male songbird. *Hormones and Behavior*, *41*(2), 203–212. https://doi.org/10.1006/hbeh.2001.1750

Soma, K. K., Schlinger, B. A., Wingfield, J. C., & Saldanha, C. J. (2003). Brain aromatase, 5α-reductase, and 5β-reductase change seasonally in wild male song sparrows: Relationship to aggressive and sexual behavior. *Journal of Neurobiology*, *56*(3), 209–221. https://doi.org/10.1002/neu.10225

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

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. *Journal of Steroid Biochemistry and Molecular Biology*, *145*, 261–272. https://doi.org/10.1016/j.jsbmb.2014.05.011

Stearns, S. C. (2000). Life history evolution: Successes, limitations, and prospects. *Naturwissenschaften*, *87*, 476–486. https://doi.org/10.1007/s001140050763

Stevenson, T. J., Prendergast, B. J., & Nelson, R. J. (2017). Mammalian seasonal rhythms: behavior and neuroendocrine substrates. In D. W. Pfaff, & M. Joëls (Eds.), *Hormones, Brain and Behavior* (Vol. 1, 3 ed., pp. 371–398). Academic Press.

Taves, M. D., Ma, C., Heimovics, S. A., Saldanha, C. J., & Soma, K. K. (2011). Measurement of steroid concentrations in brain tissue: Methodological considerations. *Frontiers in Endocrinology*, *2*, 39. https://doi.org/10.3389/fendo.2011.00039

Tiefer, L. (1970). Gonadal hormones and mating behavior in the adult golden hamster. *Hormones and Behavior*, *1*(3), 189–202. https://doi.org/10.1016/0018-506X(70)90013-9

Tiihonen, J., Räsänen, P., & Hakko, H. (1997). Seasonal variation in the occurrence of homicide in Finland. *American Journal of Psychiatry*, *154*(12), 1711–1714. https://doi.org/10.1176/ajp.154.12.1711

Trainor, B. C., Rowland, M. R., & Nelson, R. J. (2007). Photoperiod affects estrogen receptor α, estrogen receptor β and aggressive behavior. *European Journal of Neuroscience*, *26*(1), 207–218. https://doi.org/10.1111/j.1460-9568.2007.05654.x

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

Trainor, B. C., Lin, S., Finy, M. S., Rowland, M. R., & Nelson, R. J. (2007). Photoperiod reverses the effects of estrogens on male aggression via genomic and nongenomic pathways. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(23), 9840–9845. https://doi.org/10.1073/pnas.0701819104

Tsutsui, K., & Ishii, S. (1981). Effects of sex steroids on aggressive behavior of adult male Japanese quail. *General and Comparative Endocrinology*, *44*(4), 480–486. https://doi.org/10.1016/0016-6480(81)90336-1

van Goozen, S. H., Matthys, W., Cohen-Kettenis, P. T., Thijssen, J. H., & van Engeland, H. (1998). Adrenal androgens and aggression in conduct disorder prepubertal boys and normal controls. *Biological Psychiatry*, *43*(2), 156–158. https://doi.org/10.1016/S0006-3223(98)00360-6

van Goozen, S. H., van den Ban, E., Matthys, W., Cohen-Kettenis, P. T., Thijssen, J. H., & van Engeland, H. (2000). Increased adrenal androgen functioning in children with oppositional defiant disorder: A comparison with psychiatric and normal controls. *Journal of the American Academy of Child & Adolescent Psychiatry*, *39*(11), 1446–1451. https://doi.org/10.1097/00004583-200011000-00020

Vega-Rivera, N. M., Ortiz-López, L., Granados-Juárez, A., Estrada-Camarena, E. M., & Ramírez-Rodríguez, G. B. (2020). Melatonin reverses the depression-associated behaviour and regulates microglia, fractalkine expression and neurogenesis in adult mice exposed to chronic mild stress. *Neuroscience*, *440*, 316–336. https://doi.org/10.1016/j.neuroscience.2020.05.014

von Gall, C., Stehle, J. H., & Weaver, D. R. (2002). Mammalian melatonin receptors: Molecular biology and signal transduction. *Cell and Tissue Research*, *309*(1), 151–162. https://doi.org/10.1007/s00441-002-0581-4

Wacker, D. W., Schlinger, B. A., & Wingfield, J. C. (2008). Combined effects of DHEA and fadrozole on aggression and neural VIP immunoreactivity in the non-breeding male song sparrow. *Hormones and Behavior*, *53*(1), 287–294. https://doi.org/10.1016/j.yhbeh.2007.10.008

Wacker, D. W., Wingfield, J. C., Davis, J. E., & Meddle, S. L. (2010). Seasonal changes in aromatase and androgen receptor, but not estrogen receptor mRNA expression in the brain of the free-living male song sparrow, *Melospiza melodia morphna*. *Journal of Comparative Neurology*, *518*(18), 3819–3835. https://doi.org/10.1002/cne.22426

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

Wang, D., Zhang, J., & Zhang, Z. (2012). Effect of testosterone and melatonin on social dominance and agonistic behavior in male *Tscheskia triton*. *Behavioural Processes*, *89*(3), 271–277. https://doi.org/10.1016/j.beproc.2011.12.010

Weaver, D. R., Rivkees, S. A., & Reppert, S. M. (1989). Localization and characterization of melatonin receptors in rodent brain by *in vitro* autoradiography. *Journal of Neuroscience*, *9*(7), 2581–2590. https://doi.org/10.1523/JNEUROSCI.09-07-02581.1989

Weaver, D. R., Liu, C., & Reppert, S. M. (1996). Nature's knockout: The Mel1b receptor is not necessary for reproductive and circadian responses to melatonin in Siberian hamsters. *Molecular Endocrinology*, *10*(11), 1478–1487. https://doi.org/10.1210/mend.10.11.8923472

Webb, S. J., Geoghegan, T. E., & Prough, R. A. (2006). The biological actions of dehydroepiandrosterone involves multiple receptors. *Drug Metabolism Reviews*, *38*(1-2), 89–116. https://doi.org/10.1080/03602530600569877

Wehr, T. A., Duncan, W. C., Jr., Sher, L., Aeschbach, D., Schwartz, P. J., Turner, E. H., Postolache, T. T., & Rosenthal, N. E. (2001). A circadian signal of change of season in patients with seasonal affective disorder. *Archives of General Psychiatry*, *58*(12), 1108–1114. https://doi.org/10.1001/archpsyc.58.12.1108

Weil, Z. M., Bowers, S. L., & Nelson, R. J. (2007). Photoperiod alters affective responses in collared lemmings. *Behavioural Brain Research*, *179*(2), 305–309. https://doi.org/10.1016/j.bbr.2007.02.003

Weil, Z. M., Hotchkiss, A. K., Gatien, M. L., Pieke-Dahl, S., & Nelson, R. J. (2006). Melatonin receptor (MT1) knockout mice display depression-like behaviors and deficits in sensorimotor gating. *Brain Research Bulletin*, *68*(6), 425–429. https://doi.org/10.1016/j.brainresbull.2005.09.016

Weiss, C. S., & Coughlin, J. P. (1979). Maintained aggressive behavior in gonadectomized male Siamese fighting fish (*Betta splendens*). *Physiology & Behavior*, *23*(1), 173–177. https://doi.org/10.1016/0031-9384(79)90139-2

Whittier, J. M., & Crews, D. (1987). Seasonal reproduction: Patterns and control. In D. O. Norris, & R. E. Jones (Eds.), *Hormones and Reproduction in Fishes, Amphibians, and Reptiles* (pp. 385–409). Springer.

Wiley, C. J., & Goldizen, A. W. (2003). Testosterone is correlated with courtship but not aggression in the tropical buffbanded rail, *Gallirallus philippensis*. *Hormones and Behavior*, *43*(5), 554–560. https://doi.org/10.1016/S0018-506X(03)00066-7

Williams, C. L., Garcia-Reyero, N., Martyniuk, C. J., Tubbs, C. W., Bisesi, Jr., & J. H. (2020). Regulation of endocrine systems by the microbiome: Perspectives from comparative animal models. *General and Comparative Endocrinology*, *292*, 113437. https://doi.org/10.1016/j.ygcen.2020.113437

Williamson, C. M., Lee, W., Romeo, R. D., & Curley, J. P. (2017). Social context-dependent relationships between mouse dominance rank and plasma hormone levels. *Physiology & Behavior*, *171*, 110–119. https://doi.org/10.1016/j.physbeh.2016.12.038

Willis, E. O. (1972). The behavior of spotted antbirds. *Ornithological Monographs*, *10*, 1–157.

Wilsterman, K., McGuire, N. L., Calisi, R. M., & Bentley, G. E. (2019). Seasonality: hormones and behavior. In J. C. Choe (Ed.), *Encyclopedia of Animal Behavior* (2 ed., 599–612). Academic Press: Elsevier.

Wingfield, J. C., & Hahn, T. P. (1994). Testosterone and territorial behaviour in sedentary and migratory sparrows. *Animal Behaviour*, *47*(1), 77–89. https://doi.org/10.1006/anbe.1994.1009

Witt-Enderby, P. A., Bennett, J., Jarzynka, M. J., Firestine, S., & Melan, M. A. (2003). Melatonin receptors and their regulation: Biochemical and structural mechanisms. *Life Sciences*, *72*(20), 2183–2198. https://doi.org/10.1016/S0024-3205(03)00098-5

Wood, S., & Loudon, A. (2014). Clocks for all seasons: Unwinding the roles and mechanisms of circadian and interval timers in the hypothalamus and pituitary. *Journal of Endocrinology*, *222*(2), R39–R59. https://doi.org/10.1530/JOE-14-0141

Wu, Y. H., Zhou, J. N., Balesar, R., Unmehopa, U., Bao, A., Jockers, R. J, Van Heerikhuize, J., & Swaab, D. F. (2006). Distribution of MT1 melatonin receptor immunoreactivity in the human hypothalamus and pituitary gland: Colocalization of MT1 with vasopressin, oxytocin, and corticotropin-releasing hormone. *Journal of Comparative Neurology*, *499*(6), 897–910. https://doi.org/10.1002/cne.21152

Yahr, P., Coquelin, A., Martin, A., & Scouten, C. W. (1977). Effects of castration on aggression between male Mongolian gerbils. *Behavioral Biology*, *19*(2), 189–205. https://doi.org/10.1016/S0091-6773(77)91482-1

Young, J., Corpéchot, C., Haug, M., Gobaille, S., Baulieu, E. E., & Robel, P. (1991). Suppressive effects of dehydroepiandrosterone and 3 beta-methyl-androst-5-en-17-one on attack towards lactating female intruders by castrated male mice. II. *Brain neurosteroids. Biochemical and Biophysical Research Communications*, *174*(2), 892–897. https://doi.org/10.1016/0006-291x(91)91501-3

Zhang, J. X., Zhang, Z. B., & Wang, Z. W. (2001). Seasonal changes in and effects of familiarity on agonistic behaviors of rat-like hamsters (Cricetulus triton). *Ecological Research*, *16*(2), 309–317.

How to cite this article: Munley, K. M., Han, Y., Lansing, M. X., & Demas, G. E. (2022). Winter madness: Melatonin as a neuroendocrine regulator of seasonal aggression. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, 1–17. https://doi.org/10.1002/jez.2601