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Leptinergic Regulation of Vertebrate Communication Signals

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Synopsis Animal communication signals are regulated by multiple hormonal axes that ensure appropriate signal targeting, timing, and information content. The regulatory roles of steroid hormones and many peptide hormones are well understood and documented across a wide range of vertebrate taxa. Two recent studies have reported a novel function for leptin, a peptide hormone central to energy balance regulation: regulating communication signals of weakly electric fish and singing mice. With only limited evidence available at this time, a key question is just how widespread leptinergic regulation of communication signals is within and across taxa. A second important question is what features of communication signals are subject to leptinergic regulation. Here, we consider the functional significance of leptinergic regulation of animal communication signals in the context of both direct and indirect signal metabolic costs. Direct costs arise from metabolic investment in signal production, while indirect costs arise from the predation and social conflict consequences of the signal's information content. We propose a preliminary conceptual framework for predicting which species will exhibit leptinergic regulation of their communication signals and which signal features leptin will regulate. This framework suggests a number of directly testable predictions within and across taxa. Accounting for additional factors such as life history and the potential co-regulation of communication signals by leptin and glucocorticoids will likely require modification or elaboration of this model.

Leptin regulates animal communication signals

Animal communication signals are essential for survival and reproduction, but these signals also come with significant risks and costs (Bradbury and Vehrencamp 2011). Multiple hormonal axes coordinately regulate the targeting, timing, and information content of communication signals toward an optimized balance of signal costs and benefits, both for the sender and the receiver. Within this context, a rich history of research has revealed the many ways in which both steroid and peptide hormones regulate communication signals in accordance with environmental, social, and organismal conditions (Adkins-Regan 2005; Ball and Balthazart 2009; Gavassa et al. 2013).

Leptin is a relatively recent discovery in the large and diverse family of peptide hormones (Zhang et al. 1994; Campfield et al. 1995). Following its discovery, the initial and intensive focus on leptin centered on its role in mammals as an adipostat (a "fat regulator") that regulates appetite, metabolic rate and, ultimately, fat stores (Ahima and Osei 2004). Subsequent identification of the leptin peptide and leptin receptors in all major vertebrate classes led to a recent surge of comparative studies on leptin's physiological functions (Londraville et al. 2017). A growing body of comparative studies on the endocrinology of leptin in nonmammalian taxa has revealed that leptin is a pleiotropic hormone with effects on metabolic rate, glucose metabolism, energy expenditure, food intake, seasonality, development, reproduction, stress response, immunity, and behavior (Gorissen et al. 2012; Londraville et al. 2014).

Given the many ways that leptin regulates energy allocation (Denver et al. 2011), it should not be surprising that leptin also regulates animal communication signals, which can incur substantial metabolic costs

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Fig. 1 Two species where communication signals are regulated by leptin. (**A**) The weakly electric Glass Knifefish (*Eigenmannia virescens*) constantly generates electric sensory and communication signals that are sinusoidal waveforms with individual-specific frequencies of 200–600Hz. (Image courtesy of Ictiologia Universidad Católica de Oriente by Creative Commons license). (**B**) Allston's Singing Mouse (*Scotinomys teguina*): males sing complex songs consisting of a series of high-frequency notes (Image courtesy of Bret Pasch, Northern Arizona University).

(Stoddard and Salazar 2011). Surprisingly, however, only two lines of evidence have emerged to date showing that leptin regulates communication signals in accordance with the organism's available energy reserves. Recent studies have shown that leptin regulates electric communication signals in weakly electric fish (Sinnett and Markham 2015) and male courtship songs in neotropical singing mice (Burkhard et al. 2018; Giglio and Phelps 2020). These findings are made all the more interesting because they show that leptin plays this role in two vastly divergent vertebrate taxa, teleost fish and mammals, and that leptin exerts its effects on communication signals generated by divergent physiological mechanisms: electric communication signals and auditory courtship vocalizations.

The weakly electric freshwater fish *Eigenmannia virescens* (Fig. 1) generates metabolically costly electric organ discharges (EODs) that create dipole-like electric fields in the surrounding water. Weakly electric fish detect prey and nearby objects by analyzing distortions of the electric field (von der Emde 1999), and communicate with conspecifics via transient changes in EOD frequency (Hopkins 1974; Hagedorn and Heiligenberg 1985). The EOD in *E. virescens* is a sinusoidal waveform with individual-specific frequencies of 200–600 Hz (Hopkins 1974), produced by the summation of near simultaneous action potentials in the electric organ cells (Bennett 1971).

During periods of restricted food availability lasting several days, *E. virescens* reduces EOD amplitude (EODa), then restores EODa over the course of 2–3 days when ad-lib feeding is resumed. This effect is mediated by leptin: administration of exogenous leptin restores EODa in food-deprived fish, but has no effect on EODa when fish are fed ad-libitum (Sinnett and Markham 2015). The role of leptin, in this case, is to proactively reduce energetic investment in signal amplitude, as food-deprived and well-fed fish show the same transient EODa increases to both social and pharmacological challenges (Sinnett and Markham 2015).

Alston's singing mouse, *Scotinomys teguina* (Fig. 1), inhabits the high-elevation cloud forests of Central America. Males and females both produce audible high-frequency songs that are several seconds long, consisting of a lengthy series of brief high-frequency notes (Banerjee et al. 2019). Males sing more often than females, with their songs serving as courtship signals to attract mates (Pasch et al. 2011a) and as aggressive signals during male–male competition (Pasch et al. 2011b). These mice have been studied intensively as a mammalian model for the neural control of complex vocal communication (Banerjee et al. 2019; Okobi et al. 2019).

Two recent studies showed that leptin regulates song effort in male *S. teguina* in accordance with adipose energy stores (Burkhard et al. 2018; Giglio and Phelps 2020). Song effort in both studies was quantified as a compound variable identified by principal components analysis (Burkhard et al. 2018). High song effort includes singing more often, singing more quickly in response to relevant stimuli, producing longer songs, and pausing for shorter periods between song notes (Burkhard et al. 2018). Male song effort is positively correlated with adiposity and circulating leptin levels (Burkhard et al. 2018) and experimental administration of exogenous leptin increases male song effort (Giglio and Phelps 2020).

Based on these findings, leptin appears to be a key factor that regulates communication performance in accordance with the animal's available energy reserves. More specifically, these findings suggest that the primary function for leptinergic regulation of communication signals is to reduce signal metabolic costs when energy reserves are low and promote metabolic

investment in signaling when energy stores are high. The observation that leptin regulates communication signals in this manner for both fish and mice suggests that leptin might play a taxonomically broad role in regulating metabolic expenditures on communication. Two important questions emerge from these initial findings. First, how universal is leptinergic regulation of communication? That is, which species will and will not exhibit leptinergic regulation of communication signals? Second, for species in which leptin regulates communication, which signal features will leptin regulate?

Addressing these questions is facilitated by first considering the components of a communication signal's metabolic costs. The total metabolic cost of a communication signal can be partitioned into three components: production cost, predation cost, and conflict cost. Discussions of metabolic costs associated with communication signals tend to focus on the direct metabolic investment in signal production (Ophir et al. 2010; Stoddard and Salazar 2011; Dechmann et al. 2013). However, animal communication signals also can incur two categories of *indirect* metabolic costs. Indirect predation costs arise from the costs of escaping or injury if a predator detects the signal, and indirect conflict costs are incurred by combat and injury if the signal provokes attack by a conspecific or interspecific rival (Bradbury and Vehrencamp 2011; Giglio and Phelps 2020).

These three cost components are influenced by particular combinations of signal features. The signal's direct production cost is determined by its amplitude, duration, duty cycle, and efficiency. Indirect predation and conflict costs will also be affected by signal amplitude, duration, and duty cycle if these features increase the likelihood of detection by predators and hostile rivals. In addition, the predation and conflict costs are influenced also by the signal's information-coding features such as signal structure, patterning, and spectral content (Sillar et al. 2016). Importantly, these features that can be varied independently of the signal's production costs (Seyfarth et al. 2010; Akçay et al. 2015; Gustison and Townsend 2015). For example, in several songbird species, low-amplitude songs with minimal production costs serve as aggressive signals that can still precipitate costly fights (Akçay et al. 2015).

A preliminary model for investigating leptinergic regulation of communication signals

Partitioning the metabolic costs of communication into direct production costs and indirect predation and conflict costs suggests two interrelated predictions about which species will exhibit leptinergic regulation of their signals and how leptin will regulate those communication signals. First, leptinergic regulation of communication signals should be favored in taxa for which the combined metabolic costs of signaling from all components are highest. Second, the specific signal features regulated by leptin should reflect their contribution to the overall signal cost. Together these predictions suggest an initial three-dimensional framework for predicting the species in which leptinergic signal regulation should be observed, and predicting which signal characteristics leptin will regulate (Fig. 2). For species with communication signals that incur high direct production costs but low indirect predation and conflict costs, leptin should exclusively regulate the signal's direct costs (signal amplitude, duration, and/or duty cycle. In species with signals that incur low production costs, but high predation and/or conflict costs, the prediction is that leptin will regulate information-coding features of the signal in response to changing energy stores. Finally, for species in which communication signals carry both high production costs and high indirect predation/conflict costs, leptin should regulate both the information-coding features of the signal, as well as signal amplitude, duration, and/or duty cycle. The initial evidence for leptinergic signal regulation in electric fish and singing mice is consistent with this framework, but additional experimental tests would be necessary in each system to more fully test these predictions.

Signal production costs for *E. virescens* are known to be high: electric signal generation consumes as much as 30% of the daily energy budget (Salazar et al. 2013; Lewis et al. 2014). In addition, *E. virescens'* ecology and habitat suggest that the EODs of these fish also incur indirect conflict and predation costs. The potential for conflict costs is frequently present because this is a gregarious shoaling species where individuals regularly engage in agonistic interactions consisting of physical attacks and transient EOD frequency changes or EOD interruptions (Hopkins 1974; Hagedorn and Heiligenberg 1985). These transient communication features, especially interruptions, create predation risks by introducing low-frequency spectral content (Hopkins 1974) that is detectable by sympatric electroreceptive predators (Stoddard and Markham 2008). Indeed, high rates of major and minor tail damage observed in wild populations of *E. virescens* indicate that these fish suffer frequent predator attacks and conflicts with conspecifics (Hopkins 1974; Lundberg and Stager 1985).

Given these conditions, the model we propose here predicts that leptin will regulate signal production, predation, and conflict costs in *E. virescens*. We indeed

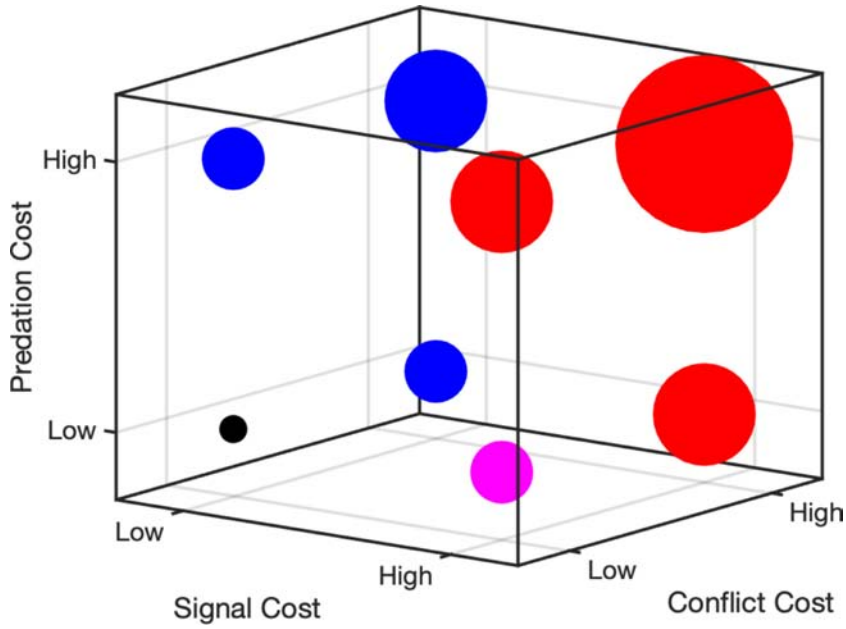

Fig. 2 A proposed schematic framework for predicting when selective pressures will favor leptinergic regulation of communication signaling effort and/or signal information content. Circle size indicates total signal metabolic cost for each combination of cost parameters, and the corresponding adaptive advantage of leptinergic signal regulation. Circle color represents a prediction of which specific signal features should be targeted by lepinergic regulation: black = no regulation; magenta = primary regulation of signaling effort; blue = primary regulation of information content; red = regulation of both signal effort and information content.

found that leptin regulates *E. virescens*' signal amplitude, a major determinant of the signal's production, conflict, and predation cost (Sinnett and Markham 2015). Our study, however, did not assess the effects of leptin on the transient information-coding features of the electric signal, such as chirps and interruptions, that occur during courtship and agonistic interactions, an area in need of future investigation.

In the case of singing mice, the potential for high indirect conflict and predation costs of communication is also present. Male vocalizations in *S. teguina* are associated with conspecific male-male aggression (Pasch et al. 2011b) and can potentially invite interspecific aggression from a closely related and larger species, *S. xerampelinus* (Pasch et al. 2013). The direct production cost of these vocalizations has not been directly measured, but the long song durations (4–10 s), duty cycle greater than 50%, and high dominant signal frequencies (> 20 kHz) suggest a significant metabolic investment in song production.

In this case also, our model predicts that leptin will regulate signal production costs in *S. teguina*, as well as signal conflict costs. Indeed, several parameters of song production in male *S. teguina* are correlated with adipose stores and leptin titers (Burkhard et al. 2018), and these same song features are also regulated by exogenous leptin injections (Giglio and Phelps 2020). In this case, leptin regulated multiple information-coding song features including the song frequency (number of songs during the testing interval), song duration, and number of notes per song. Technical barriers precluded measurement of song amplitude, a centrally important component of direct production cost. Though leptin's effects on song production costs are not yet precisely known, these findings do suggest that leptin regulates song production cost. Additionally, the observed changes in song structure suggest that leptin is altering the song's informational content, thereby potentially regulating song conflict and predation costs.

Additional factors beyond the initial model

A simplified framework such as we outline here will, of course, require revision and/or elaboration as additional data become available, particularly as the breadth of comparative studies increases. Two additional factors that will likely need to be incorporated into any model of leptinergic signal regulation are differences in life history, and the potential interactions of leptin and glucocorticoids in regulating communication signals.

Life history strategies

Experimental findings from two species of electric fish suggest that, during food restriction, falling leptin titers may not downregulate signal amplitude for all species. In the weakly electric fish *Brachyhypopomus gauderio*,

food restriction does not reduce the baseline EODa of mature males, and food-restricted males actually produce larger transient increases in EODa during social challenges than do well-fed fish (Gavassa and Stoddard 2012). While this study did not test the effects of leptin on EOD characteristics, the fact that food restriction caused a situationally dependent increase in EODa suggests that leptin might regulate EODa in opposite directions and under different circumstances in *E. virescens* and *B. gauderio*.

Two possible interpretations might explain why decreased food availability (and presumably leptin) would cause an overall reduction of EODa in *E. virescens*, but increase EODa specifically only during social challenges in *B. gauderio*. The first interpretation is consistent with the framework we have suggested: differential direct investment in signal production between these species. The daily metabolic costs of EOD production in weakly electric fish studied to date is quite high in general, but the fraction of the daily energy budget devoted to EOD production is much higher for *E. virescens* than for *B. gauderio* (Salazar and Stoddard 2008; Lewis et al. 2014; Markham et al. 2016). A major reason for this difference is that *B. gauderio* produces EODs at variable rates of 10–100 Hz and can slow EOD rate to conserve energy if necessary. *E. virescens*, on the other hand, generates EODs at stable individually specific rates of 200–600 Hz.

A second hypothesis is that different EODa responses to metabolic stress in *E. virescens* and *B. gauderio* are a result of differences in life history and reproductive strategy. *E. virescens* are iteroparous multi-season breeders (Kirschbaum 1979; Hagedorn and Heiligenberg 1985; Kramer 1987) whereas *B. gauderio* are semelparous single-season breeders (Silva et al. 2003). Iteroparous species typically reduce reproductive efforts (including costly communication signals) during stressful periods, presumably to survive until environmental conditions improve before resuming reproductive efforts (Wingfield and Sapolsky 2003). Semelparous species typically continue reproductive behaviors during periods of stress, in some cases engaging in terminal investments in reproduction (Cluttonbrock 1984). Thus, *E. virescens* may reduce EODa to conserve energy and await better food availability while *B. gauderio* responds to dietary energy shortfalls with a situationally specific terminal investment in reproduction.

The effects of a particular hormone can diverge significantly between closely related species with different life histories, sometimes even having opposite effects (Goodson et al. 2009; Kelly and Goodson 2013). Comparative studies across multiple electric fish species with different reproductive strategies would enable a direct test of whether leptin's effects on electric communication signals is indeed a function of reproductive strategy. This seems a distinct possibility, and one that would require an extension or revision of the initial model we have proposed here.

Coregulation of communication signals by leptin and glucocorticosteroids

The framework we propose here also might need expansion to consider the potentially interactive or complementary functions of leptin and glucocorticosteroids (GCs) in regulating communication signals during metabolic stress. Circulating GC titers rise in response to a wide variety of stressors (Wingfield et al. 1998; Sapolsky et al. 2000) including food restriction (Lynn et al. 2003). Elevated GC levels exert different effects on communication signals across taxa, suppressing communication in some species but upregulating communication in other species (Leary and Baugh 2020). Even within a species, GCs can have opposite effects. For example, in midshipman fish (*Porichthys notatus*) elevated GCs increase vocalization effort in territorial males (Remage-Healey and Bass 2004) but decrease vocalization effort in females and non-territorial males (Remage-Healey and Bass 2007).

Because both leptin and GCs regulate communication signals in response to energy shortfalls, additional investigation will be necessary to determine their respective roles. One possibility is that leptin plays a complementary role to GCs in facilitating responses to metabolic stress, with leptin and GCs operating on different timescales. Elevation of circulating GC levels in response to food restriction can occur in as little as two hours (Lynn et al. 2003), signaling an energetic shortfall before prolonged food restriction begins to deplete adipose or hepatic energy reserves thereby reducing circulating leptin levels. Thus, GCs could regulate communication signals to respond appropriately to acute food restriction whereas leptin's role is to regulate signals only after prolonged energy shortfalls decrease adipose and/or hepatic glycogen energy stores below some minimum threshold.

Convergence and divergence in the physiology of leptinergic signal regulation

Existing evidence suggests that leptin exerts its effects through both common and divergent mechanisms across taxa. For instance, the primary source of leptin in mammals is adipose tissue, whereas adipocytes contribute little or no leptin in teleosts. Instead, the highest levels of leptin expression in teleosts are from liver, with some expression also in brain, gonads, muscle, and kidney (Won and Borski 2013; Londraville et al. 2014; Deck et al. 2017). These differences are potentially

important because tissue-specific sources of circulating leptin (i.e., adipocytes vs. liver) will determine the conditions under which leptin titers change and thereby determine which internal or external cues elicit leptinergic regulation of communication signals. For example, if leptin is released exclusively by adipocytes, then it will probably only regulate communication in response to changes in fat stores. In contrast, gonadal, hepatic, or central release of leptin would be expected to regulate communication in response to a wider range of internal and external cues.

Currently, available evidence suggests that leptin regulates communication signals through diverse physiological mechanisms across taxa. Social communication signals represent the combined contributions of central control networks and peripheral effector tissues. Leptin is known to exert effects both on central neural and hormonal systems as well as regulating the physiology of peripheral tissues (Londraville et al. 2014). Leptin could therefore regulate signal production, conflict, and predation costs through regulation of central mechanisms controlling signal investment and information coding, as well as regulation of the peripheral effector tissues that control the pattern, amplitude, and spectral content of signal output.

The observed effects of leptin on song structure and effort in singing mice likely depends on regulation of the well-characterized central neural networks and motor pattern generators that sequence and execute the song components (Okobi et al. 2019). This foundational knowledge sets the stage to examine the central mechanisms through which leptin controls song frequency, structure, and effort. It would be interesting to find out whether leptin also regulates peripheral effectors such as the laryngeal and expiratory musculature to further control signal metabolic costs. Similarly, central networks controlling electric signaling have also been defined to varying degrees in several species of electric fish (Silva et al. 2013; Perrone and Silva 2018; Comas et al. 2019) highlighting the possibility of mechanistic studies investigating leptinergic control over information-coding patterns of electric signaling.

In weakly electric fish, peripheral mechanisms in the electric organ cells (electrocytes) regulate EOD waveform characteristics, thereby controlling both the direct metabolic costs of communication (Markham et al. 2016), and the signal's spectral characteristics that encode important social information (Gavassa et al. 2013). Our recent data have shown that the muscle-derived electrocytes in *E. virescens* express membrane-bound leptin receptors that colocalize with the electrocyte's voltage-gated Na^+ channels (unpublished observations). These findings indicate that leptin regulates EODa, at least in part, by acting directly on the electrocytes—perhaps to control the magnitude of voltage-gated Na^+ currents, a known mechanism for regulating EODa in this species (Markham et al. 2013). We are also exploring the possibility that leptin regulates EODa by interacting with centrally regulated hormonal axes that regulate pituitary melanocortin hormones to control EODa in *E. virescens* and other electric fish species (Markham et al. 2009a, 2009b, 2013).

Expanding the comparative scope

In the context of understanding leptin's full effects on regulating communication signal costs, we are left with two intriguing but incomplete pictures from studies in electric fish and singing mice. A complete comparison of leptin's functions in these two systems would be aided by examining the effects of leptin on the indirect information-coding costs of electric signals in weakly electric fish, and the effects of leptin on the direct metabolic investment in song production by mice. To expand from these initial studies to a broader understanding of leptinergic signal regulation, however, additional comparative studies in other taxa are critically important. Most informative will be comparisons between taxa subject to different signal production costs, conflict costs, and predation costs.

The Gymnotiform order of South American electric fish includes more than 200 species with a broad range of electric signal characteristics, ecologies, and life histories. Given this diversity, comparative studies examining the effects of signal production, conflict, and predation costs on leptinergic signal regulation could prove especially fruitful in this system. Direct signal production costs should vary considerably across species: species-specific signal frequencies range from ~10 Hz to more than 2000 Hz with a wide range of signal amplitudes across species (citation). Indirect signal conflict costs also will be different between species: social structures range from fiercely solitary to gregarious and shoaling (e.g., Oestreich and Zakon 2005; Stamper et al. 2010; Batista et al. 2012), thereby offering variation in signal conflict costs. Similarly, the broad geographic and habitat distribution of Gymnotiform species provides natural variation in indirect signal predation costs (Dunlap et al. 2016; Stoddard et al. 2019).

The outcome variables of interest in electric fish are readily tractable and can be reliably measured. Precisely calibrated measurements of signal amplitude can be readily recorded from freely swimming fish in the laboratory (Stoddard et al. 2003), and continuous recordings of electric signaling in social groups over many days is possible (Tallarovic and Zakon 2002), even in natural stream settings (Henninger et al. 2018; Madhav et al.

2018). Straightforward respirometry methods can be used concurrently with electric signal recordings to directly measure the metabolic costs of signal production (Salazar and Stoddard 2008; Lewis et al. 2014).

Similar advantages are possible through comparative studies in avian and anuran species as well. The direct metabolic costs of signal production for several species of passerine birds are known, as is the case for several anuran species. In both cases signal costs vary over more than an order of magnitude (Stoddard and Salazar 2011) and detailed data on many species' social structure and predation risk are available. Informative comparisons are also possible in experimentally accessible mammalian models. Sonic and/or ultrasonic communication is now documented in several murine species, and in many cases the social functions of these vocalizations are now well understood (e.g., Holy and Guo 2005). The combination of social manipulations with respirometry and calibrated signal analyses should allow a comparative examination of leptin's role in regulating vocalizations across species with different direct signal costs, different social conditions, and under different predation pressures.

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References

Adkins-Regan E. 2005. Hormones and Animal Social Behavior. Princeton: Princeton University Press.

Ahima RS, Osei SY. 2004. Leptin signaling. Physiol Behav 81:223–41.

Akçay Ç, Anderson RC, Nowicki S, Beecher MD, Searcy WA. 2015. Quiet threats: soft song as an aggressive signal in birds. Anim Behav 105:267–74.

Ball GF, Balthazart J. 2009. Endocrinology of animal communication: behavioral. In: Squire L.R (ed.). Encyclopedia of Neuroscience. Oxford: Academic Press. p. 981–9.

Banerjee A, Phelps SM, Long MA. 2019. Singing mice. Curr Biol 29:R190–1.

Batista G, Zubizarreta L, Perrone R, Silva A. 2012. Non-sex-biased dominance in a sexually monomorphic electric fish: fight structure and submissive electric signalling. Ethology 118:398–410.

Bennett MVL. 1971. Electric organs. In Hoar W. S, Randall D. J (ed.), Fish Physiology. New York, NY: Academic Press. p. 347–491.

Bradbury JW, Vehrencamp SL. 2011. Principles of Animal Communication. Sunderland, MA: Sinauer Associates.

Burkhard TT, Westwick RR, Phelps SM. 2018. Adiposity signals predict vocal effort in Alston's singing mice. Proc. Royal Society B: Biological Sci. 285:20180090.

Campfield LA, Smith FJ, Guisez Y, Devos R, Burn P. 1995. Recombinant mouse OB protein: evidence for a peripheral signal linking adiposity and central neural networks. Science 269:546–9.

Cluttonbrock TH. 1984. Reproductive effort and terminal investment in iteroparous animals. Am Nat 123:212–29.

Comas V, Langevin K, Silva A, Borde M. 2019. Distinctive mechanisms underlie the emission of social electric signals of submission in *Gymnotus omarorum*. J Exp Biol 222: jeb195354.

Dechmann DKN, Wikelski M, Van Noordwijk HJ, Voigt CC, Voigt-Heucke SL. 2013. Metabolic costs of bat echolocation in a non-foraging context support a role in communication. Frontiers Physiol 4:64.

Deck CA, Honeycutt JL, Cheung E, Reynolds HM, Borski RJ. 2017. Assessing the functional role of leptin in energy homeostasis and the stress response in vertebrates. Frontiers in Endocrinol 8:63.

Denver RJ, Bonett RM, Boorse GC. 2011. Evolution of leptin structure and function. Neuroendocrinology 94:21–38.

Dunlap KD, Tran A, Ragazzi MA, Krahe R, Salazar VL. 2016. Predators inhibit brain cell proliferation in natural populations of electric fish, Brachyhypopomus occidentalis. Proc of the Royal Society B: Biological Sci 283:20152113.

Gavassa S, Goldina A, Silva AC, Stoddard PK. 2013. Behavioral ecology, endocrinology and signal reliability of electric communication. J Exp Biol 216:2403–11.

Gavassa S, Stoddard PK. 2012. Food restriction promotes signaling effort in response to social challenge in a short-lived electric fish. Horm Behav 62:381–8.

Giglio EM, Phelps SM. 2020. Leptin regulates song effort in Neotropical singing mice (*Scotinomys teguina*). Anim Behav 167:209–19.

Goodson JL, Kabelik D, Schrock SE. 2009. Dynamic neuromodulation of aggression by vasotocin: influence of social context and social phenotype in territorial songbirds. Biol Lett 5: 554–6.

Gorissen M, Bernier NJ, Manuel R, de Gelder S, Metz JR, Huising MO, Flik G. 2012. Recombinant human leptin attenuates stress axis activity in common carp (*Cyprinus carpio* L.). Gen Comp Endocrinol 178:75–81.

Gustison ML, Townsend SW. 2015. A survey of the context and structure of high- and low-amplitude calls in mammals. Anim Behav 105:281–8.

Hagedorn M, Heiligenberg W. 1985. Court and spark – electric signals in the courtship and mating of gymnotoid fish. Anim Behav 33:254–65.

Henninger J, Krahe R, Kirschbaum F, Grewe J, Benda J. 2018. Statistics of natural communication signals observed in the

wild identify important yet neglected stimulus regimes in weakly electric fish. J. Neurosci. 38:5456–65.
Holy TE, Guo Z. 2005. Ultrasonic songs of male mice. PLoS Biol 3:e386.
Hopkins CD. 1974. Electric communication: functions in the social behavior of *Eigenmannia virescens*. Behaviour 50:270–304.
Kelly AM, Goodson JL. 2013. Behavioral relevance of species-specific vasotocin anatomy in gregarious finches. Frontiers in Neurosci. 7:242.
Kirschbaum F. 1979. Reproduction of the weakly electric fish *Eigenmannia virescens* (Rhamphichtyidae, Teleostei) in captivity: Control of gonadal recrudescence and regression by environmental factors. Behav Ecol Sociobiol 4:331–55.
Kramer B. 1987. The sexually dimorphic jamming avoidance response in the electric fish *Eigenmannia* (Teleostei, Gymnotiformes). J Exp Biol 130:39–62.
Leary CJ, Baugh AT. 2020. Glucocorticoids, male sexual signals, and mate choice by females: implications for sexual selection. Gen Comp Endocrinol 288:113354.
Lewis JE, Gilmour KM, Moorhead MJ, Perry SF, Markham MR. 2014. Action potential energetics at the organismal level reveal a trade-off in efficiency at high firing rates. J Neurosci 34:197–201.
Londraville RL, Macotela Y, Duff RJ, Easterling MR, Liu Q, Crespi EJ. 2014. Comparative endocrinology of leptin: assessing function in a phylogenetic context. Gen Comp Endocrinol 203:146–57.
Londraville RL, Prokop JW, Duff RJ, Liu Q, Tuttle M. 2017. On the molecular evolution of leptin, leptin receptor, and endospanin. Frontiers in Endocrinology 8:58.
Lundberg JG, Stager JC. 1985. Microgeographic diversity in the Neotropical knife-fish *Eigenmannia macrops* (Gymnotiformes, Sternopygidae). Environ Biol Fishes 13:173–81.
Lynn SE, Breuner CW, Wingfield JC. 2003. Short-term fasting affects locomotor activity, corticosterone, and corticosterone binding globulin in a migratory songbird. Horm Behav 43:150–7.
Madhav MS, Jayakumar RP, Demir A, Stamper SA, Fortune ES, Cowan NJ. 2018. High-resolution behavioral mapping of electric fishes in Amazonian habitats. Sci Rep 8:5830.
Markham MR, Allee SJ, Goldina A, Stoddard PK. 2009. Melanocortins regulate the electric waveforms of gymnotiform electric fish. Horm Behav 55:306–13.
Markham MR, Ban Y, McCauley AG, Maltby R. 2016. Energetics of sensing and communication in electric fish: a blessing and a curse in the Anthropocene? Integr Comp Biol 56: 889–900.
Markham MR, Kaczmarek LK, Zakon HH. 2013. A sodium-activated potassium channel supports high-frequency firing and reduces energetic costs during rapid modulations of action potential amplitude. J Neurophysiol 109:1713–23.
Markham MR, McAnelly ML, Stoddard PK, Zakon HH. 2009b. Circadian and social cues regulate ion channel trafficking. PLoS Biol 7:e1000203.
Oestreich J, Zakon HH. 2005. Species-specific differences in sensorimotor adaptation are correlated with differences in social structure. J Comparative Physiol A 191:845–56.
Okobi DE, Jr., Banerjee A, Matheson AMM, Phelps SM, Long MA. 2019. Motor cortical control of vocal interaction in Neotropical singing mice. Science 363:983–8.
Ophir AG, Schrader SB, Gillooly JF. 2010. Energetic cost of calling: general constraints and species-specific differences. J Evol Biol 23:1564–9.
Pasch B, Bolker BM, Phelps SM. 2013. Interspecific dominance via vocal interactions mediates altitudinal zonation in neotropical singing mice. Am Nat 182:E161–73.
Pasch B, George AS, Campbell P, Phelps SM. 2011. Androgen-dependent male vocal performance influences female preference in Neotropical singing mice. Anim Behav 82:177–83.
Pasch B, George AS, Hamlin HJ, Guillette LJ, Jr., Phelps SM. 2011. Androgens modulate song effort and aggression in Neotropical singing mice. Horm Behav 59:90–7.
Perrone R, Silva AC. 2018. Status-dependent vasotocin modulation of dominance and subordination in the weakly electric fish *Gymnotus omarorum*. Frontiers in Behav Neuroscience 12:1.
Remage-Healey L, Bass AH. 2004. Rapid, hierarchical modulation of vocal patterning by steroid hormones. J Neurosci 24:5892–900.
Remage-Healey L, Bass AH. 2007. Plasticity in brain sexuality is revealed by the rapid actions of steroid hormones. J Neurosci 27:1114–22.
Salazar VL, Krahe R, Lewis JE. 2013. The energetics of electric organ discharge generation in gymnotiform weakly electric fish. J Exp Biol 216:2459–68.
Salazar VL, Stoddard PK. 2008. Sex differences in energetic costs explain sexual dimorphism in the circadian rhythm modulation of the electrocommunication signal of the gymnotiform fish *Brachyhypopomus pinnicaudatus*. J Exp Biol 211:1012–20.
Sapolsky RM, Romero LM, Munck AU. 2000. How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. Endocr Rev 21:55–89.
Seyfarth RM, Cheney DL, Bergman T, Fischer J, Zuberbühler K, Hammerschmidt K. 2010. The central importance of information in studies of animal communication. Anim Behav 80:3–8.
Sillar KT, Picton L, Heitler WJ. 2016. The Neuroethology of Predation and Escape. Chichester, Hoboken, NJ: John Wiley & Sons.
Silva A, Quintana L, Galeano M, Errandonea P. 2003. Biogeography and breeding in Gymnotiformes from Uruguay. Environ Biol Fishes 66:329–38.
Silva AC, Perrone R, Zubizarreta L, Batista G, Stoddard PK. 2013. Neuromodulation of the agonistic behavior in two species of weakly electric fish that display different types of aggression. J Exp Biol 216:2412–20.
Sinnett PM, Markham MR. 2015. Food deprivation reduces and leptin increases the amplitude of an active sensory and communication signal in a weakly electric fish. Horm Behav 71:31–40.
Stamper SA, Carrera GE, Tan EW, Fugere V, Krahe R, Fortune ES. 2010. Species differences in group size and electrosensory interference in weakly electric fishes: implications for electrosensory processing. Behav Brain Res 207: 368–76.
Stoddard PK, Markham MR. 2008. Signal cloaking by electric fish. Bioscience 58:415–25.
Stoddard PK, Markham MR, Salazar VL. 2003. Serotonin modulates the electric waveform of the gymnotiform electric fish *Brachyhypopomus pinnicaudatus*. J Exp Biol 206:1353–62.

Stoddard PK, Salazar VL. 2011. Energetic cost of communication. J Exp Biol 214:200–5.

Stoddard PK, Tran A, Krahe R. 2019. Predation and crypsis in the evolution of electric signaling in weakly electric fishes. Frontiers Ecol and Evol 7:264.

Tallarovic SK, Zakon HH. 2002. Electrocommunication signals in female brown ghost electric knifefish, *Apteronotus leptorhynchus*. J Comp Physiol, A 188:649–57.

von der Emde G. 1999. Active electrolocation of objects in weakly electric fish. J Exp Biol 202:1205–15.

Wingfield JC, Maney DL, Breuner CW, Jacobs JD, Lynn S, Ramenofsky M, Richardson RD. 1998. Ecological Bases of Hormone—behavior interactions: the "emergency life history stage." Am Zool 38:191–206.

Wingfield JC, Sapolsky RM. 2003. Reproduction and resistance to stress: when and how. J Neuroendocrinol 15: 711–24.

Won ET, Borski RJ. 2013. Endocrine regulation of compensatory growth in fish. Frontiers in Endocrinol 4: 74.

Zhang Y, Proenca R, Maffei M, Barone M, Leopold L, Friedman JM. 1994. Positional cloning of the mouse obese gene and its human homologue. Nature 372: 425–32.