

RESEARCH ARTICLE

Monoaminergic integration of diet and social signals in the brains of juvenile spadefoot toads

Sabrina S. Burmeister^{1,2,‡}, Verónica G. Rodríguez Moncalvo^{*,1} and Karin S. Pfennig¹

ABSTRACT

Social behavior often includes the production of species-specific signals (e.g. mating calls or visual displays) that evoke context-dependent behavioral responses from conspecifics. Monoamines are important neuromodulators that have been implicated in context-dependent social behavior, yet we know little about the development of monoaminergic systems and whether they mediate the effects of early life experiences on adult behavior. We examined the effects of diet and social signals on monoamines early in development in the plains spadefoot toad (*Spea bombifrons*), a species in which diet affects the developmental emergence of species recognition and body condition affects the expression of adult mating preferences. To do so, we manipulated the diet of juveniles for 6 weeks following metamorphosis and collected their brains 40 min following the presentation of either a conspecific or a heterospecific call. We measured levels of monoamines and their metabolites using high pressure liquid chromatography from tissue punches of the auditory midbrain (i.e. torus semicircularis), hypothalamus and preoptic area. We found that call type affected dopamine and noradrenaline signaling in the auditory midbrain and that diet affected dopamine and serotonin in the hypothalamus. In the preoptic area, we detected an interaction between diet and call type, indicating that diet modulates how the preoptic area integrates social information. Our results suggest that the responsiveness of monoamine systems varies across the brain and highlight preoptic dopamine and noradrenaline as candidates for mediating effects of early diet experience on later expression of social preferences.

KEY WORDS: Monoamines, Body condition, Social preferences, Anurans, Behavioral plasticity, Species recognition

INTRODUCTION

Social behavior can be defined broadly as any interaction between conspecifics in which one individual benefits, and it often includes the production of species-specific signals that evoke context-dependent responses from conspecifics (Insel and Fernald, 2004). The context-dependent expression of social behavior is particularly important for the adaptive expression of mating preferences (Cummings, 2015). For example, mate preferences may vary

depending on predation risk (Kim et al., 2009), social experience (Kodric-Brown and Nicoletto, 2001) or physiological state (Cotton et al., 2006; Lynch et al., 2006).

In the plains spadefoot toad, *Spea bombifrons* (Cope 1863), body condition (mass relative to length) modifies the expression of mating preferences: females in poor body condition are more likely to prefer the mating calls of the heterospecific *Spea multiplicata* (Cope 1863) than are females in good condition (Pfennig, 2007). While hybrid offspring have reduced fertility and fecundity, they develop faster, thus producing a net benefit for poor-condition females living in fast-drying ponds (Pfennig, 2007; Pfennig and Simovich, 2002). In contrast, good-condition females are more likely to produce faster developing offspring and, therefore, are less likely to benefit from hybridizing. Thus, females in good body condition more consistently prefer conspecifics. While it is still unknown how plasticity in these mating preferences develops, early experiences with diet may play an important role (Pfennig et al., 2013). This species is therefore ideal for evaluating the neural mechanisms linking diet and condition with the development of social preferences.

Because neuromodulators act to alter the efficacy of synaptic transmission, they are poised to play an important role in context-dependent behavior. The monoamines – noradrenaline (NA, norepinephrine), dopamine (DA) and serotonin (5-HT, 5-hydroxytryptamine) – share a number of functions, including sensory processing, attention, arousal and synaptic plasticity (Hurley et al., 2004; Maney, 2013; Sara, 2009), that affect social behavior broadly, and its context-dependent expression, specifically. For example, NA plays an important role in auditory discrimination of conspecific signals in songbirds (Appeltants et al., 2002; Castelino and Schmidt, 2010; Lynch and Ball, 2008; Maney, 2013) and 5-HT modifies sensory processing of conspecific social signals in mammals (Hurley and Hall, 2011; Hurley and Pollak, 2005) and fish (Deemyad et al., 2013). In the basal forebrain, monoamines are sensitive to physiological conditions, such as gonadal development, that influence social interactions (Chu and Wilczynski, 2002; Etgen et al., 1999; Hull et al., 1995). In addition, it has been found that early dietary experiences can modify the development of monoamine signaling (Levin, 2006). Thus, monoamines may provide a link between diet and the later development of social preferences.

Our long-term goal is to understand how early life experiences affect the development of context-dependent mating preferences in plains spadefoot toads. In the present study, we examined monoamine levels in response to diet and social signals in the brains of juveniles. We measured monoamines in the auditory midbrain, which is responsible for processing social signals in anurans (Wilczynski and Endepols, 2006), the hypothalamus, which is central to the control of food intake and satiety in vertebrates (Fischer and O'Connell, 2017), and the preoptic area, a central part of the social decision-making network (O'Connell and

¹Department of Biology, University of North Carolina, Chapel Hill, NC 27599, USA.

²Curriculum in Neurobiology, University of North Carolina, Chapel Hill, NC 27599, USA.

[‡]Present address: School of Interdisciplinary Science, General Sciences Building, Room 105, McMaster University, Hamilton, ON, Canada L8N 3Z5.

[‡]Author for correspondence (sburmeister@unc.edu)

 S.S.B., 0000-0001-5612-692X

Hofmann, 2012) that has been implicated in mating preferences (Martinez and Petrulis, 2013).

MATERIALS AND METHODS

Subjects

To generate our subjects, we bred four pairs of *S. bombifrons* males and females. All adults were wild-caught from sympatric populations near Portal, AZ, USA. The resulting tadpoles were fed tadpole chow *ad libitum*. At metamorphosis, juvenile toads were randomly assigned to either a high-food ($n=15$) or low-food ($n=15$) diet. We interspersed siblings among treatment groups such that any treatment effect would not be confounded by a family effect. However, because of small sample sizes, we were unable to account for family effects in our models. Because our subjects were only one generation removed from wild populations, they still maintained significant levels of genetic variation. Nonetheless, the use of four families may reduce the generalizability of our results beyond the families included here. Because live juveniles cannot be sexed, both males and females were randomly included in our sample (sex ratios of sibships are generally 50:50; K.P., unpublished data). From

metamorphosis until 6 weeks of age, juveniles on the high-food diet were fed five ~3 mm crickets daily while those on the low-food diet were fed five ~3 mm crickets three times per week. At 6 weeks of age, we measured body mass and snout–vent length (SVL). We calculated body condition for individuals relative to others of their species by regressing mass on SVL and using the resulting residuals as our measure of body condition (Pfennig, 2007).

At 6 weeks post-metamorphosis, we presented individual toads with either 40 min of *S. bombifrons* mating calls or 40 min of *S. multiplicata* mating calls in a dark acoustic chamber as previously described (Rodríguez Moncalvo et al., 2013). We tested animals in a dry environment (on moist towel, but no standing water). The call stimuli were identical to those used previously (Pfennig, 2007), and consisted of calls that were average for the call characters of each species (Pfennig, 2000, 2007). For these sympatric populations, the pulse and call rates of the two species show no overlap (Pfennig, 2000) and are, thus, readily distinguishable (see Pfennig, 2007, for audio files). The stimuli were synthesized with Audacity 1.2.4 sound editor software by generating a triangular pulse by applying the ‘fade out’ effect to a pure sine tone. These pulses were repeated

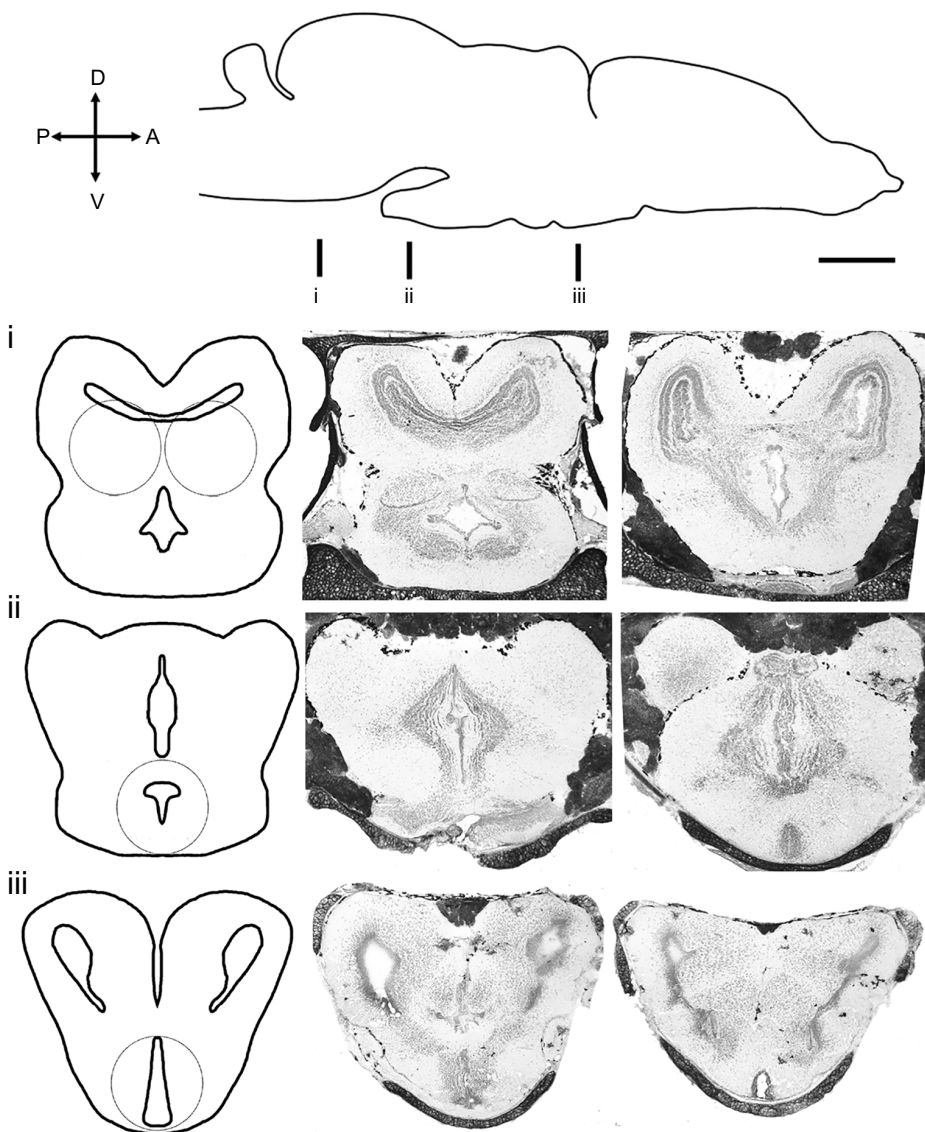


Fig. 1. Schema of the juvenile spadefoot toad brain and diagrams of transverse sections illustrating the brain regions studied. Vertical bars indicate the starting point of each 300 μm transverse section from which we micropunched the brain regions of interest, shown in corresponding rows (i, auditory midbrain; ii, hypothalamus; iii, preoptic area). The left side of each row shows schematic diagrams of the caudal position of each micropunch (indicated by circles), and the photomicrographs of the Thionine-stained sections represent the ‘before’ (center) and ‘after’ (right) sections of each punch. Scale bar, 300 μm .

to create a single call and the calls were repeated to produce a 29 s call bout for each species (Pfennig, 2007).

Quantification of monoamines

Immediately following the 40 min sound exposure, we decapitated each animal, quickly dissected its cranium, embedded it in OCT embedding medium (Sakura, Finetek, Torrance, CA, USA), and froze it in liquid nitrogen (see Rodriguez Moncalvo et al., 2013, for details). We stored craniums at -80°C until sectioning. We sectioned craniums in the coronal plane in a caudal-to-rostral direction at -15°C , obtaining 300 μm brain sections for microdissection. We collected 350 μm diameter punches from the auditory midbrain (including posterior, laminar and magnocellular nuclei of the torus semicircularis), hypothalamus (including ventral hypothalamus, dorsal hypothalamus and posterior tuberculum) and preoptic area, following Rodriguez Moncalvo et al. (2013) (Fig. 1). For the auditory midbrain, we combined punches from the two hemispheres to create one representative sample, while we took single punches from the midline for the hypothalamus and preoptic area. During punch collection, we maintained the section at -20°C . We expelled the tissue punches into microcentrifuge tubes containing 100 μl of mobile phase and 0.1 $\text{pg } \mu\text{l}^{-1}$ of an internal standard (see Rodriguez Moncalvo et al., 2013, for details) and rapidly froze them on dry ice. We stored all samples at -80°C until high pressure liquid chromatography (HPLC) analysis.

While the neuroanatomy of monoaminergic systems has not been well studied in juvenile anurans, the limited amount of data suggest that these systems are well developed early in post-metamorphosis and are consistent with adult distributions (Rodriguez Moncalvo et al., 2013). Therefore, based on the adult anatomical studies (reviewed in Rodriguez Moncalvo et al., 2013), we infer that our auditory midbrain samples contained terminals for NA, DA and 5-HT fibers. Our hypothalamus tissue sample likely included terminals for NA, DA and 5-HT fibers, as well as DA cell bodies and, potentially, 5-HT cell bodies. Finally, the preoptic area sample likely included terminals for NA, DA and 5-HT fibers, as well as DA cell bodies.

We used HPLC with electrochemical detection to determine tissue concentrations of NA and its metabolite MHPG (3-methoxy-4-hydroxyphenylglycol), DA and its metabolite DOPAC (3,4-dihydroxyphenylacetic acid), and 5-HT (5-hydroxytryptamine) and its metabolite 5HIAA (5-hydroxyindoleacetic acid) (see Rodriguez Moncalvo et al., 2013, for details). Tissue levels of monoamines reflect amounts that are both stored (in cells and fibers) and released,

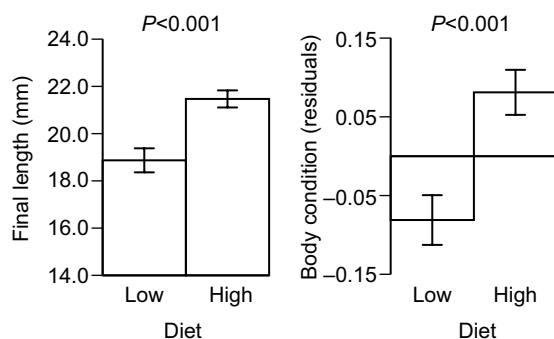


Fig. 2. Diet manipulation affects growth and body condition. Toads were fed a high- or low-food diet. Growth was assessed by final length; body condition is represented by residuals of mass regressed on length. Data are means \pm s.e.m. There were 15 animals in each diet treatment; P -values correspond to two-tailed t -tests.

whereas levels of metabolites are thought to primarily reflect the amount of monoamine that is released from nerve terminals (Meiser et al., 2013; Moore, 1986). We were not able to normalize concentrations per μg of protein because the protein content of each sample was too low to be detected using standard protein assays. If anything, our inability to normalize for protein concentration would decrease our ability to detect differences among groups because the protein content of the punches should account for error due to variation in section thickness or placement of the punch. Thus, our results likely represent conservative estimates of differences among groups.

Statistical analysis

We used t -tests to examine the effects of diet on final length (SVL) and body condition. We used two-way ANOVA to examine the

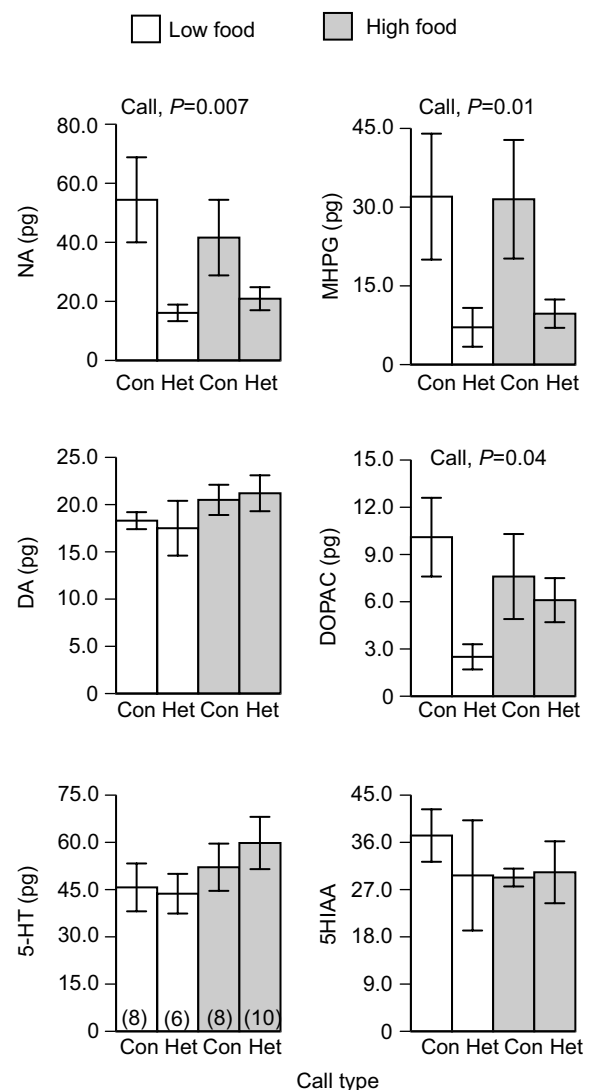


Fig. 3. The type of mating call heard affects noradrenergic and dopaminergic signaling in the auditory midbrain, while diet manipulation has no detectable effect. NA, noradrenaline; DA, dopamine; 5-HT, serotonin; MHPG, 3-methoxy-4-hydroxyphenylglycol (NA metabolite); DOPAC, 3,4-dihydroxyphenylacetic acid (DA metabolite); 5HIAA, 5-hydroxyindoleacetic acid (5-HT metabolite); con, conspecific; het, heterospecific. Data are means \pm s.e.m. The number of animals in each group is indicated parenthetically; P -values correspond to two-way ANOVA.

effects of diet, call type and their interaction on concentrations of monoamines for each brain region separately. For the hypothalamus (MHPG, DOPA) and preoptic area (MHPG), some metabolite concentrations fell below detectable limits for our HPLC system and so are not reported here.

RESULTS

Six-week old toads on the high-food diet were longer ($t_{28}=4.16$, $P=0.0003$) and had better body condition ($t_{28}=3.8$, $P=0.0007$) than toads on the low-food diet (Fig. 2).

In the auditory midbrain, we found a strong relationship between the call type presented and levels of DA and NA: call type affected levels of NA ($P=0.007$) and its metabolite MHPG ($P=0.01$) as well as the DA metabolite DOPAC ($P=0.04$) (Fig. 3, Table 1). Diet had no detectable effect on monoamine levels in the auditory midbrain (Fig. 3, Table 1). Taken together, we conclude that DA and NA release in the auditory midbrain responded to intrinsic features of the call (e.g. call energy) in a way that could contribute to encoding information about call type.

In the hypothalamus, animals receiving the high-food diet had lower levels of DA ($P=0.02$), 5-HT ($P=0.005$) and the 5-HT metabolite 5HIAA ($P=0.01$) than animals on the low-food diet (Fig. 4, Table 1). Even though the hypothalamus is known to be acoustically sensitive (Allison, 1992), monoamine levels here were not influenced by the type of call heard.

Finally, in the preoptic area, we detected a significant interaction between diet and call type for both NA ($P=0.03$) and DA ($P=0.04$), indicating that diet affected how the preoptic area responded to call type (Fig. 5, Table 1). Intriguingly, diet reversed the relationship between call type and NA/DA levels in a manner that is reminiscent of the relationship between body condition and female mate choice behavior in adults (Pfennig, 2007). That is, under conditions that would promote a conspecific preference in adults (high-food diet), NA and DA levels were higher in response to the conspecific call, whereas under conditions that would promote a heterospecific preference in adults (low-food diet), NA and DA levels were high in response to the heterospecific call.

DISCUSSION

Overall, the effects of diet and social signals on monoamine levels showed neuroanatomical heterogeneity in the brains of juvenile spadefoot toads. We found that monoamine levels were sensitive to call type within the auditory midbrain, to diet in the hypothalamus, and to both calls and diet in the preoptic area. In the preoptic area, the interaction between diet and call type reflected the relationship between body condition and female mating preference in adults.

In the auditory midbrain, we found changes in the concentration of both metabolites (MHPG, DOPAC) and neurotransmitter (NA, but not DA), suggesting changes in synaptic transmission (Meiser et al., 2013; Moore, 1986), with greater neurotransmitter release in response to the conspecific call compared with the heterospecific call. In the preoptic area, we only found evidence for changes in neurotransmitter concentration (NA, DA), but not metabolites (DOPAC; MHPG was not measured). Increases in neurotransmitter concentration likely reflect changes in monoaminergic tone, i.e. the increased production and release of the neurotransmitter over a longer period of time. Changes in monoaminergic tone often occur when longer-term modulation of neurotransmission is required (e.g. Krenz et al., 2014). These two patterns are consistent with the factors that influenced the monoamines in the two brain areas. That is, auditory processing of call information in the midbrain may not depend on changes in neurotransmitter tone, whereas integration of physiological cues such as food availability with social information is more likely to involve longer-term modulatory mechanisms.

Amphibians, unlike most vertebrates, have a larval stage followed by metamorphosis that leads to a juvenile in the form of the adult. The cytoarchitecture of tadpole and adult brains is qualitatively similar (Lannoo, 2000), although the metamorphic transition from aquatic to terrestrial hearing is characterized by plasticity in the auditory system (Boatright-Horowitz and Simmons, 1997; Simmons, 2015). Once metamorphosis is complete, the juvenile anuran brain appears to be similar anatomically and functionally to that of adults. This is supported by the fact that auditory discrimination and phonotaxis appear early in life (Baugh and Ryan, 2010; Pfennig et al., 2013), gradually increase in frequency through post-metamorphic growth, and are expressed in their full

Table 1. Results from two-way ANOVA examining the effects of diet (high food versus low food), mating call type (conspecific versus heterospecific) and their interaction on levels of monoamines and their metabolites

	Diet			Call			Diet×call		
	<i>F</i>	d.f.	<i>P</i>	<i>F</i>	d.f.	<i>P</i>	<i>F</i>	d.f.	<i>P</i>
Auditory midbrain									
NA	0.15	1,28	0.70	8.5	1,28	0.007	0.75	1,28	0.40
MHPG	0.01	1,28	0.90	7.2	1,28	0.01	0.03	1,28	0.86
DA	2.5	1,28	0.13	0.00	1,28	0.97	0.15	1,28	0.70
DOPAC	0.07	1,28	0.79	4.8	1,28	0.04	2.1	1,28	0.15
5-HT	1.98	1,28	0.17	0.13	1,28	0.72	0.37	1,28	0.55
5HIAA	0.36	1,28	0.55	0.30	1,28	0.59	0.49	1,28	0.49
Hypothalamus									
NA	0.05	1,28	0.82	1.68	1,28	0.21	0.65	1,28	0.43
DA	6.4	1,28	0.02	0.67	1,28	0.42	1.15	1,28	0.29
5-HT	9.24	1,28	0.005	1.8	1,28	0.19	<0.01	1,28	0.98
5HIAA	7.1	1,28	0.01	1.86	1,28	0.18	0.01	1,28	0.94
Preoptic area									
NA	0.17	1,26	0.69	0.15	1,26	0.70	5.0	1,26	0.03
DA	0.01	1,26	0.91	0.10	1,26	0.76	4.9	1,26	0.04
DOPAC	0.04	1,26	0.85	2.1	1,26	0.16	0.15	1,26	0.70
5-HT	<0.01	1,26	0.97	2.2	1,26	0.15	2.2	1,26	0.15
5HIAA	3.8	1,26	0.06	1.82	1,26	0.19	0.52	1,26	0.48

NA, noradrenaline; MHPG, 3-methoxy-4-hydroxyphenylglycol (NA metabolite); DA, dopamine; DOPAC, 3,4-dihydroxyphenylacetic acid (DA metabolite); 5-HT, serotonin; 5HIAA, 5-hydroxyindoleacetic acid (5-HT metabolite)

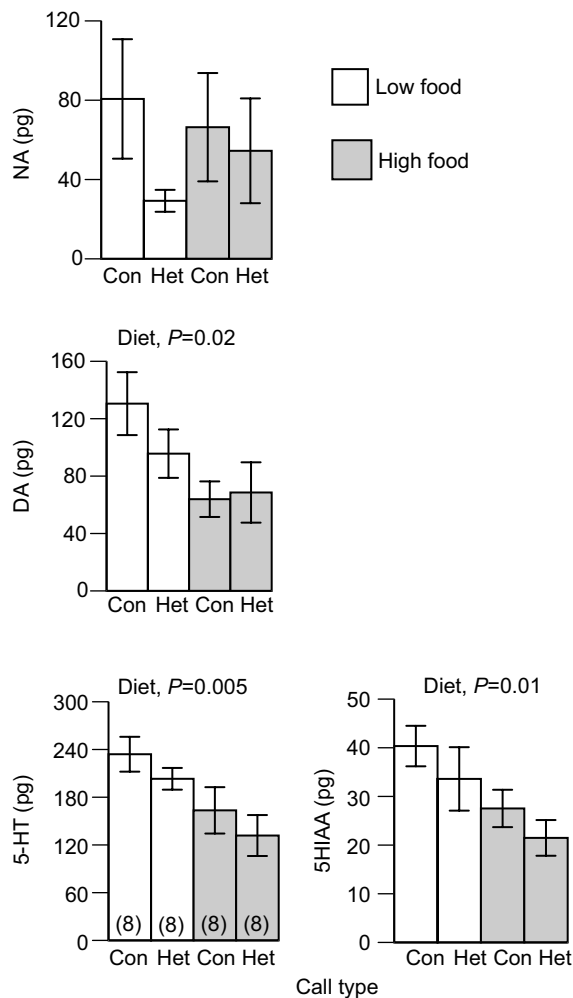


Fig. 4. Diet manipulation affects concentrations of DA, 5-HT and 5HIAA in the hypothalamus, while mating call type has no effect. Data are means \pm s.e.m. The number of animals in each group is indicated parenthetically; *P*-values correspond to two-way ANOVA.

form at sexual maturity (Baugh and Ryan, 2010). In plains spadefoot toads, the emergence of call preference (conspecific versus heterospecific) is modified by diet (Pfennig et al., 2013), indicating plasticity in the ontogeny of social behavior in this species. Our finding that diet modified the call-evoked levels of monoamines in the preoptic area suggests that the preoptic area could be an important site for mediating the developmental emergence of mating preference and/or context-dependent behavior in adults.

While the preoptic area is a highly conserved node of the social behavior network of vertebrates (Newman, 1999; O'Connell and Hofmann, 2012), relatively little is known about its role in social behavior in anurans. Because the preoptic area is acoustically sensitive (Allison, 1992) and its neuroendocrine cells respond to social signals (Burmeister and Wilczynski, 2005), it has long been thought critical in mediating the effects of social interactions on gonadal development (Brzoska and Obert, 1980; Burmeister and Wilczynski, 2000), as part of the so-called audioendocrine circuit (Wilczynski and Endepols, 2006). However, the preoptic area might also have direct influence on motor circuits through its descending projections to the midbrain and spinal cord (Sánchez-Camacho et al., 2001). Indeed, in males, the preoptic area is critical for

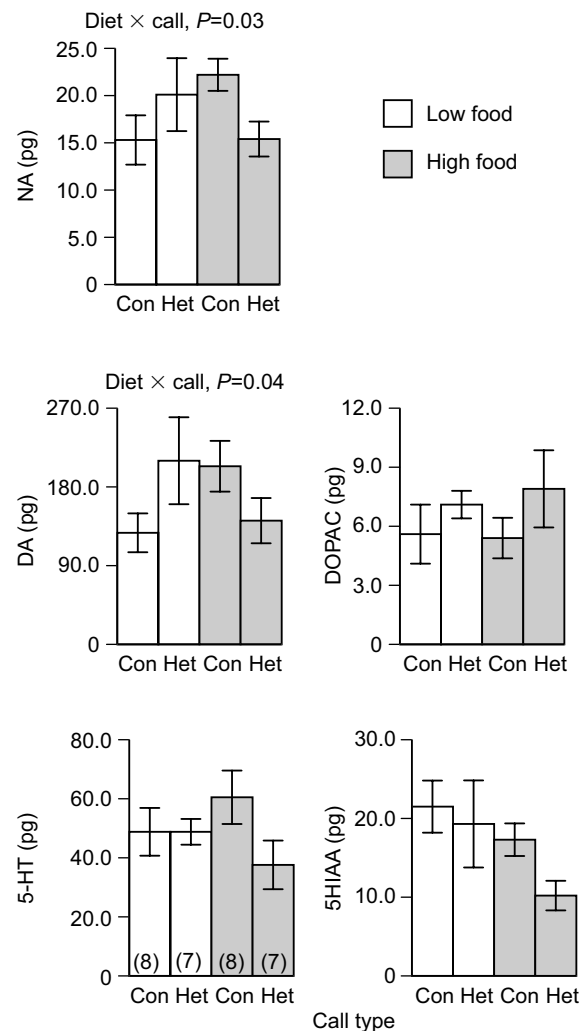


Fig. 5. In the preoptic area, diet manipulation reverses the relative response of NA and DA to mating call type. Data are means \pm s.e.m. The number of animals in each group is indicated parenthetically; *P*-values correspond to two-way ANOVA.

producing vocal responses to mating calls (Schmidt, 1984), and it is required for selective phonotaxis in females (Walkowiak et al., 1999). Furthermore, neural responses of the preoptic area – but not other brain regions examined – correlate with the expression of mating preference in both túngara frogs (Chakraborty and Burmeister, 2015) and spadefoot toads (present study). A role for the preoptic area in mating preference of anurans is consistent with data from mammals (Henley et al., 2011; Martinez and Petrucci, 2013). However, whether the changes in NA and DA signaling we observed in the preoptic area are causally related to selective social responses awaits further study.

In the hypothalamus, we found that diet restriction was associated with increased levels of DA, 5-HT and its metabolite 5HIAA, with smaller animals having higher levels of these monoamines. In mammals, 5-HT produced by the raphe nuclei acts as a satiety signal when released in the hypothalamus (Lam et al., 2010; Voigt and Fink, 2015) and diet can affect the development of 5-HT signaling (Hassanain and Levin, 2002). While little is known about the control of appetite in anurans, the neuroanatomy of both the hypothalamus (Dominguez et al., 2013, 2014) and 5-HT systems (Zhao and Debski, 2005) is highly conserved in vertebrates and they are likely to be functionally similar. Indeed, our results are

consistent with a causal relationship between 5-HT and satiety in mammals (Voigt and Fink, 2015): we found that toads in the high-food group, which (we infer) had greater levels of satiety, had lower concentrations of hypothalamic serotonin.

Monoamines have been shown to be important in auditory processing in mammals (Hurley et al., 2004) and birds (Castelino and Schmidt, 2010; Maney, 2013), where they increase the signal to noise ratio in such a way as to enhance the processing of social signals. While the auditory midbrain of anurans (torus semicircularis) has been studied extensively in the context of social communication (Wilczynski and Endepols, 2006), our study is the first to identify a potentially important role for monoamines. The auditory midbrain is believed to be important for audio-motor integration (Wilczynski and Endepols, 2006). Descending projections from the forebrain, including the septum, striatum, preoptic area and hypothalamus, are thought to modulate processes within the torus semicircularis that are, in turn, capable of generating behavioral responses to mating calls (reviewed in Wilczynski and Endepols, 2006). However, in the present study, monoaminergic responses to mating calls in the auditory midbrain lacked plasticity of the kind that reflects the behavioral plasticity we observed in response to diet. At least with regards to monoaminergic signaling then, the auditory midbrain does not appear to be a candidate for the development of social preferences as mediated by physiological cues such as diet.

In summary, we examined the effects of diet and social signals on monoamines in a species where diet has the potential to influence the development of social preferences. Our results identified the preoptic area as a candidate for mediating the plasticity of social behavior, while the hypothalamus and auditory midbrain showed no plasticity in their response to diet and mating calls, respectively. By using a broad approach that examined multiple neuromodulators across multiple brain regions, we have created a strong foundation for future investigations of the early development of social preferences.

Acknowledgements

We thank Keith W. Sockman for use of his HPLC system and S.B. Southerland for his expertise in measuring monoamines.

Competing interests

The authors declare no competing or financial interests.

Author contributions

Conceptualization: S.S.B., K.S.P., V.G.R.M.; Methodology: S.S.B., K.S.P., V.G.R.M.; Formal analysis: S.S.B., V.G.R.M.; Investigation: V.G.R.M.; Writing - original draft: S.S.B.; Writing - review & editing: K.S.P., V.G.R.M.; Funding acquisition: K.S.P.

Funding

This work was supported by the National Institutes of Health [1DP2 OD004436-01 to K.S.P.]. Deposited in PMC for release after 12 months.

References

- Allison, J. D. (1992). Acoustic modulation of neural activity in the preoptic area and ventral hypothalamus of the green treefrog (*Hyla cinerea*). *J. Comp. Physiol. A* **171**, 387-395.
- Appeltants, D., Del Negro, C. and Balthazart, J. (2002). Noradrenergic control of auditory information processing in female canaries. *Behav. Brain Res.* **133**, 221-235.
- Baugh, A. T. and Ryan, M. J. (2010). The development of sexual behavior in túngara frogs (*Physalaemus pustulosus*). *J. Comp. Psychol.* **124**, 66-80.
- Boatright-Horowitz, S. S. and Simmons, A. M. (1997). Transient "deafness" accompanies auditory development during metamorphosis from tadpole to frog. *Proc. Nat. Acad. Sci. USA* **94**, 14877-14882.
- Brzoska, J. and Obert, H.-J. (1980). Acoustic signals influence the hormone production of the testes in the grass frog. *J. Comp. Physiol.* **140**, 25-29.

- Burmeister, S. S. and Wilczynski, W. (2000). Social signals influence hormones independently of calling behavior in the treefrog (*Hyla cinerea*). *Horm. Behav.* **38**, 201-209.
- Burmeister, S. S. and Wilczynski, W. (2005). Social signals regulate gonadotropin-releasing hormone neurons in the green treefrog. *Brain Behav. Evol.* **65**, 26-32.
- Castelino, C. B. and Schmidt, M. F. (2010). What birdsong can teach us about the central noradrenergic system. *J. Chem. Neuroanat.* **39**, 96-111.
- Chakraborty, M. and Burmeister, S. S. (2015). Effects of estradiol on neural responses to social signals in female túngara frogs. *J. Exp. Biol.* **218**, 3671-3677.
- Chu, J. and Wilczynski, W. (2002). Androgen effects on tyrosine hydroxylase cells in the Northern leopard frog, *Rana pipiens*. *Neuroendocrinology* **76**, 18-27.
- Cotton, S., Small, J. and Pomiankowski, A. (2006). Sexual selection and condition-dependent mate preferences. *Curr. Biol.* **16**, R755-R765.
- Cummings, M. E. (2015). The mate choice mind: studying mate preference, aversion and social cognition in the female poeciliid brain. *Anim. Behav.* **103**, 249-258.
- Deemyad, T., Metzen, M. G., Pan, Y. and Chacron, M. J. (2013). Serotonin selectively enhances perception and sensory neural responses to stimuli generated by same-sex conspecifics. *Proc. Nat. Acad. Sci. USA* **110**, 19609-19614.
- Domínguez, L., Morona, R., González, A. and Moreno, N. (2013). Characterization of the hypothalamus of *Xenopus laevis* during development. I. The alar regions. *J. Comp. Neurol.* **521**, 725-759.
- Domínguez, L., González, A. and Moreno, N. (2014). Characterization of the hypothalamus of *Xenopus laevis* during development. II. The basal regions. *J. Comp. Neurol.* **522**, 1102-1131.
- Etgen, A. M., Chu, H.-P., Fiber, J. M., Karkanias, G. B. and Morales, J. M. (1999). Hormonal integration of neurochemical and sensory signals governing female reproductive behavior. *Behav. Brain Res.* **105**, 93-103.
- Fischer, E. K. and O'Connell, L. A. (2017). Modification of feeding circuits in the evolution of social behavior. *J. Exp. Biol.* **220**, 92-102.
- Hassanain, M. and Levin, B. E. (2002). Dysregulation of hypothalamic serotonin turnover in diet-induced obese rats. *Brain Res.* **929**, 175-180.
- Henley, C. L., Nunez, A. A. and Clemens, L. G. (2011). Hormones of choice: The neuroendocrinology of partner preference in animals. *Front Neuroendocrinol.* **32**, 146-154.
- Hull, E. M., Du, J., Lorrain, D. S. and Matuszewich, L. (1995). Extracellular dopamine in the medial preoptic area: implications for sexual motivation and hormonal control of copulation. *J. Neurosci.* **15**, 7465-7471.
- Hurley, L. M. and Hall, I. C. (2011). Context-dependent modulation of auditory processing by serotonin. *Hear. Res.* **279**, 74-84.
- Hurley, L. M. and Pollak, G. D. (2005). Serotonin modulates responses to species-specific vocalizations in the inferior colliculus. *J. Comp. Physiol. A* **191**, 535-546.
- Hurley, L. M., Devilbiss, D. M. and Waterhouse, B. D. (2004). A matter of focus: monoaminergic modulation of stimulus coding in mammalian sensory networks. *Curr. Opin. Neurobiol.* **14**, 488-495.
- Insel, T. R. and Fernald, R. D. (2004). How the brain processes social information: searching for the social brain. *Annu. Rev. Neurosci.* **27**, 697-722.
- Kim, T. W., Christy, J. H., Dennenmoser, S. and Choe, J. C. (2009). The strength of a female mate preference increases with predation risk. *Proc. Roy. Soc. Lond. B* **276**, 775-780.
- Kodric-Brown, A. and Nicoletto, P. F. (2001). Age and experience affect female choice in the guppy (*Poecilia reticulata*). *Am. Nat.* **157**, 316-323.
- Krenz, W.-D. C., Parker, A. R., Rodgers, E. W. and Baro, D. J. (2014). Dopaminergic tone persistently regulates voltage-gated ion current densities through the D1R-PKA axis, RNA polymerase II transcription, RNAi, mTORC1, and translation. *Front Cell Neurosci.* **8**, 39.
- Lam, D. D., Garfield, A. S., Marston, O. J., Shaw, J. and Heisler, L. K. (2010). Brain serotonin system in the coordination of food intake and body weight. *Pharm. Biochem. Behav.* **97**, 84-91.
- Lannoo, M. J. (2000). Integration: nervous and sensory systems. In *Tadpoles: The Biology of Anuran Larvae* (ed. R. W. McDiarmid and R. Altig), p. 458. Chicago, The University of Chicago Press.
- Levin, B. E. (2006). Metabolic imprinting: critical impact of the perinatal environment on the regulation of energy homeostasis. *Phil. Trans. Roy. Soc. Lond. B* **361**, 1107-1121.
- Lynch, K. S. and Ball, G. F. (2008). Noradrenergic deficits alter processing of communication signals in female songbirds. *Brain Behav. Evol.* **72**, 207-214.
- Lynch, K. S., Crews, D., Ryan, M. J. and Wilczynski, W. (2006). Hormonal state influences aspects of female mate choice in the túngara frog (*Physalaemus pustulosus*). *Horm. Behav.* **49**, 450-457.
- Maney, D. L. (2013). The incentive salience of courtship vocalizations: Hormone-mediated 'wanting' in the auditory system. *Hear. Res.* **305**, 19-30.
- Martinez, L. A. and Petrusis, A. (2013). The medial preoptic area is necessary for sexual odor preference, but not sexual solicitation, in female Syrian hamsters. *Horm. Behav.* **63**, 606-614.
- Meiser, J., Weindl, D. and Hiller, K. (2013). Complexity of dopamine metabolism. *Cell Comm. Signal.* **11**, 34.

- Moore, K. E.** (1986). Drug-induced changes in the efflux of dopamine and serotonin metabolites from the brains of freely moving rats. *Ann. N.Y. Acad. Sci.* **473**, 303-320.
- Newman, S. W.** (1999). The medial extended amygdala in male reproductive behavior. A node in the mammalian social behavior network. *Ann. N.Y. Acad. Sci.* **877**, 242-257.
- O'Connell, L. A. and Hofmann, H. A.** (2012). Evolution of a vertebrate social decision-making network. *Science* **336**, 1154-1157.
- Pfennig, K. S.** (2000). Female spadefoot toads compromise on mate quality to ensure conspecific matings. *Behav. Ecol.* **11**, 220-227.
- Pfennig, K. S.** (2007). Facultative mate choice drives adaptive hybridization. *Science* **318**, 965-967.
- Pfennig, K. S. and Simovich, M. A.** (2002). Differential selection to avoid hybridization in two toad species. *Evolution* **56**, 1840-1848.
- Pfennig, K. S., Rodriguez Moncalvo, V. G. and Burmeister, S. S.** (2013). Diet alters species recognition in juvenile toads. *Biol. Lett.* **9**, 20130599.
- Rodriguez Moncalvo, V. G., Burmeister, S. S. and Pfennig, K. S.** (2013). Social signals increase monoamine levels in the tegmentum of juvenile Mexican spadefoot toads (*Spea multiplicata*). *J. Comp. Physiol. A* **199**, 681-691.
- Sánchez-Camacho, C., Marín, O., Ten Donkelaar, H. J. and González, A.** (2001). Descending supraspinal pathways in amphibians: I. a dextran amine tracing study of their cells of origin. *J. Comp. Neurol.* **434**, 186-208.
- Sara, S. J.** (2009). The locus coeruleus and noradrenergic modulation of cognition. *Nat. Rev. Neurosci.* **10**, 211-223.
- Schmidt, R. S.** (1984). Neural correlates of frog calling: preoptic area trigger of "mating calling". *J. Comp. Physiol. A* **154**, 847-853.
- Simmons, A. M.** (2015). Representation of particle motion in the auditory midbrain of a developing anuran. *J. Comp. Physiol. A* **201**, 681-689.
- Voigt, J.-P. and Fink, H.** (2015). Serotonin controlling feeding and satiety. *Behav. Brain Res.* **277**, 14-31.
- Walkowiak, W., Berlinger, M., Schul, J. and Gerhardt, H. C.** (1999). Significance of forebrain structures in acoustically guided behaviour in anurans. *Eur. J. Morph.* **37**, 177-181.
- Wilczynski, W., Endepols, H.** (2006). Central auditory pathways in anuran amphibians: the anatomical basis of hearing and sound communication. In *Hearing and Sound Communication in Amphibians* (ed. P. M. Narins, A. S. Feng and R. R. Fay), pp. 221-249. New York: Springer.
- Zhao, B. and Debski, E. A.** (2005). Serotonergic reticular formation cells in *Rana pipiens*: categorization, development, and tectal projections. *J. Comp. Neurol.* **487**, 441-456.