Activity of FoxP2-positive neurons correlate with tadpole begging behavior

Sarah C. Ludington, Jordan E. McKinney, Julie M. Butler, Maiah Gaines-Richardson, Lauren A. O'Connell*

Department of Biology, Stanford University, Stanford, CA 94305, USA

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*To whom correspondence should be addressed:
Lauren A. O'Connell
Department of Biology
Stanford University
371 Jane Stanford Way
Stanford, CA 94305
loconnel@stanford.edu

Abstract

Motor function is a critical aspect of social signaling in a wide range of taxa. The transcription factor FoxP2 is well studied in the context of vocal communication in humans, mice, and songbirds, but its role in regulating social signaling in other vertebrate taxa is unclear. We examined the distribution and activity of FoxP2-positive neurons in tadpoles of the mimetic poison frog (*Ranitomeya imitator*). In this species, tadpoles are reared in isolated plant nurseries and are aggressive to other tadpoles. Mothers provide unfertilized egg meals to tadpoles that perform a begging display by vigorously vibrating back and forth. We found that FoxP2 is widely distributed in the tadpole brain and parallels the brain distribution in mammals, birds, and fishes. We then tested the hypothesis that FoxP2-positive neurons would have differential activity levels in begging or aggression contexts compared to non-social controls. We found that FoxP2-positive neurons showed increased activation in the striatum and cerebellum only during begging. Overall, this work suggests a generalizable role for FoxP2 in social signaling across terrestrial vertebrates.

Introduction

In species where parents provision offspring, infant signaling can be important for obtaining food. Begging behavior generally involves coordination of motor circuits, such as vocalization in chicks [1–3], vibrational displays in amphibian tadpoles [4,5], and chemical and motor signals in insect larvae [6,7]. There is a rich theoretical literature on the evolutionary conflict between offspring signaling and parental investment [8,9], which has been experimentally investigated mostly in birds [10–12]. While the behavioral and physiological ecology of begging has received much attention, the neural basis underlying begging behavior is relatively unknown. Investigating the neural circuits and gene networks that regulate offspring signaling would establish a mechanistic view on how begging behavior evolves from ancestral neural features. This perspective would complement the existing theoretical models of how and when begging signals evolve.

Transcription factor Forkhead Box P2 protein (FoxP2) is associated with motor processes related to social behavior in many species. Research interest in FOXP2 surged when a mutation was linked to speech and language impairments in humans [13] (human FOXP2 and non-human FoxP2 homologs are upper and lowercase, respectively). The mutation of a critical residue in the DNA-binding domain of the human FOXP2 (the R553H mutation) causes difficulty with fine rapid movements of the mouth and face that impair speech [14]. FOXP2 truncations and intragenic deletions also manifest in language and speech impairments [15–17]. Individuals carrying FOXP2 disruptions are at risk for other phenotypes such as difficulties feeding in infancy and low performance in receptive and expressive language assessments [18]. A conserved role for FoxP2 has been extended to mice [19] and birds [20]. For example, FoxP2 manipulations influence vocalizations emitted by birds [20–22] and mice [23–25]. Functional studies in humans, mice, and birds point to the role of FoxP2 in the development and function of

corticostriatal and corticocelebellar circuits important for motor control [13,26,27]. Despite the research emphasis on vocal communication, FoxP2 manipulations in mice lead to altered social interactions, parental care, and aggression [28,29], suggesting a broad role for FoxP2 in coordinating socio-motor behaviors.

Frogs use both vocal and non-vocal signaling for social interactions [30,31], but the role of FoxP2 in frog communication has not yet been investigated, to our knowledge. The whole-body distribution of FoxP2 has been described in the early development of *Xenopus*, with expression in the larval fore-, mid-, and hindbrain [32]. Given expression of FoxP2 in the tadpole brain, we reasoned that FoxP2 may be involved in tadpole signaling. Specifically, we tested the hypothesis that FoxP2 is associated with non-vocal begging signals of tadpoles. We tested this hypothesis in the mimetic poison frog (*Ranitomeya imitator*), where tadpoles beg parents for unfertilized egg meals by vigorously vibrating back and forth [33]. Tadpoles are reared in isolated nurseries where they are aggressive to intruder tadpoles [4,34]. We first mapped the neural distribution of FoxP2 in the *R. imitator* tadpole brain and then compared the activity of FoxP2-positive neurons across begging, aggressive, and control animals. We predicted that FoxP2-positive neurons would have higher activity in begging tadpoles.

Methods

Animals

All *Ranitomeya imitator* tadpoles used were bred from our laboratory colony [35]. Adult *R. imitator* females from actively reproducing breeding pairs were used as stimulus animals in the begging context. A conspecific tadpole was used as a stimulus in the aggression context. All procedures were approved by the Stanford University Animal Care and Use Committee (Protocol #33097).

Behavior

We randomly assigned tadpoles (Gosner stage 30-34, no forelimb development and minimal hindlimb development) into one of three experimental groups: begging to a reproductive adult female (begging, N=14); fighting a smaller conspecific tadpole (aggression, N=15), or exposed to a novel object with no begging or aggression displayed (a metal bolt, N=15). All behavior trials were conducted between 09:00 and 12:00 hours. Tadpoles were placed into individual square arenas (5 x 5 x 5 cm) filled with 50 mL of conditioned water (Josh's Frogs R/O Rx, Owosso, MI). Tadpoles were recorded from above using GoPro cameras (GoPro HERO7 Black, 1080p, 240 fps). Each tadpole acclimated for 10 min in the arena. Then, the stimulus was introduced to the arena and behavior was recorded for 30 min. Stimuli were then removed from the arena and tadpoles were placed in the dark for 15 minutes to minimize post stimulus neural activity. Tadpoles were then anesthetized with topical 20% benzocaine and euthanized by decapitation.

Videos were scored using BORIS software [36] by an observer uninformed of tadpole identity. Begging was quantified by the number and duration of each begging bout. Aggression was quantified by the number and duration of attacks towards the stimulus tadpole.

Immunohistochemistry

Whole tadpole heads were fixed with 4% paraformaldehyde (PFA) in 1X phosphate buffered saline (PBS) at 4°C overnight, rinsed in 1X PBS, and transferred to a 30% sucrose solution for cryoprotection at 4°C overnight. Tadpole heads were then embedded in mounting media (Tissue-Tek® O.C.T. Compound, Electron Microscopy Sciences, Hatfield, PA, USA) and stored at -80°C until cryosectioning at 15 µm into three series. Sections were thaw-mounted onto SuperFrost Plus microscope slides (VWR International, Randor, PA, USA) and then stored at -80°C until immunohistochemistry.

We used double-label fluorescence immunohistochemistry to detect FoxP2 and phosphorylated ribosomes (pS6, phospho-S6, a proxy of neural activity [37]) as previously described [38]. Slides were incubated overnight in a mix of both primary antibodies [rabbit anti-pS6 (Invitrogen, cat #44-923G) at 1:500 and goat anti-FoxP2 (Abcam, cat #AB1307) at 1:500 in 2% normal donkey, 0.3% TritonX-100, 1X PBS]. Following several washes, slides were incubated in a mix of fluorescent secondary antibodies (1:200 Alexa 488 donkey anti-goat and 1:200 Alexa 568 donkey anti-rabbit in 2% normal donkey serum, 0.3% TritonX-100, 1X PBS) for two hours. Slides were then rinsed in water and cover slipped using Vectashield Hardset Mounting Medium with DAPI (Vector Laboratories, Burlingame, CA, USA) and stored at 4°C. FoxP2 was restricted to cell nuclei and additional antibody characterization can be found in Supplementary Materials.

Fluorescence microscopy and cell counting

Brain sections were imaged on a Leica compound fluorescent microscope with a QImaging Retiga 2000R camera. Brain regions containing FoxP2 were identified using DAPI-stained nuclei while referencing a poison frog brain atlas [38]. FIJI software [39] was used to measure the area of the nucleus accumbens, striatum, and cerebellum within a single hemisphere across several sections. The number of FoxP2-positive cells, pS6-positive cells, and colocalized cells were quantified within each area using the “Cell Counter” function. Due to tissue quality, not all sections were counted for every individual.

Data analysis

All statistics and figures were generated in R Studio (version 1.1.442) running R (version 3.5.2). We used the glmmTMB R package [40] to analyze cell count data with generalized linear mixed models. For FoxP2-positive and pS6/FoxP2 colocalized cells, we ran separate models using a negative binomial distribution appropriate for count data. Model fit was confirmed using

DHARMa [41]. For both models, we tested the main effects of group, brain region, and their interaction. Tadpole identity was included as a random variable to account for repeated sampling of brain regions within individuals. For colocalization data, we included the number of colocalized cells as the independent variable and the number of FoxP2 cells as a weight in the model. For FoxP2 cell numbers, the log of brain region area was included as an offset. We then followed each model with the Anova.glmmTMB function for reported statistical values. When there was a significant interaction between group and brain region, we ran a post-hoc test with the emmeans R package (version 1.5.3) and used a fdr-correction for multiple hypothesis testing.

Results

Neural distribution of FoxP2

We observed a broad distribution of FoxP2-positive cells throughout the tadpole brain (Figure 1). The highest densities of FoxP2-positive cells were found in the subpallial forebrain, optic tectum, thalamus, and cerebellum. Notably, there were many FoxP2 cells in regions linked to sensory processing, such as the olfactory bulb (chemosensory), torus semicircularis (acoustic processing), and optic tectum (vision).

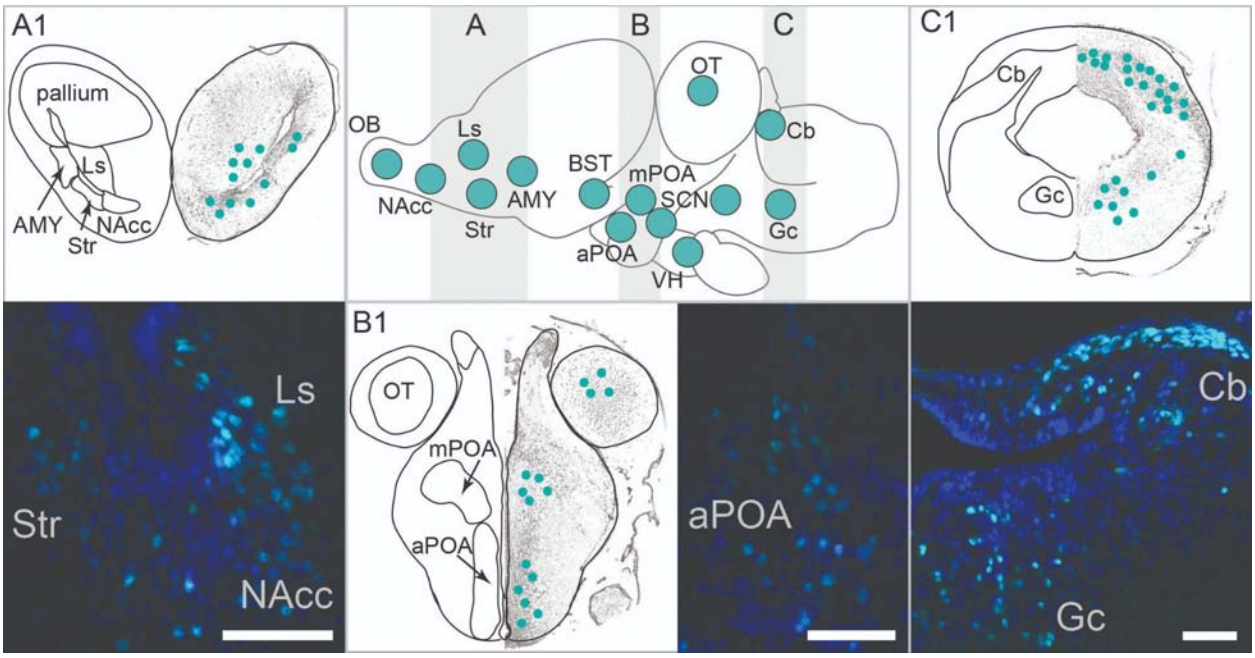

Figure 1. Neural distribution of FoxP2 in amphibians is similar to other vertebrates. FoxP2 is widely distributed throughout the amphibian brain, including the subpallial forebrain (A), midbrain (B), and a few hindbrain regions (C). The center sagittal brain schematic (rostral is to the left) shows brain regions (green) with FoxP2 positive cells. Gray boxes represent areas of interest for more detailed neuroanatomy and micrographs (A1-C1), where green dots represent qualitative presence of FoxP2. Micrographs show FoxP2-positive cells (cyan) and DAPI-stained nuclei (blue); scale bar is 20 µm. The complete neural distribution for FoxP2 can be found in Supplementary Materials. Abbreviations: AMY, amygdala; aPOA, anterior preoptic area; BST, bed nucleus of the stria terminalis; Cb, cerebellum; Gc, central gray; Ls, lateral septum; mPOA, magnocellular preoptic area; NAcc, nucleus accumbens; OB, olfactory bulb; OT, optic tectum; SCN, suprachiasmatic nucleus; Str, striatum; VH ventral hypothalamus.

FOXP2-positive neurons are more active during begging

We investigated whether FoxP2-positive neuron activity is associated with begging behavior by quantifying the proportion of FoxP2-positive cells that colocalized with the pS6 marker of neural activity in tadpoles showing begging, aggression, or exposed to a novel object (asocial control) (Figure 2). We focused our quantification efforts on the basal ganglia (nucleus accumbens and striatum) and cerebellum given their robust expression of FoxP2 in mice and birds [42] and functional studies suggesting FoxP2-associated vocalization deficits are due to altered corticostriatal and corticocerebellar circuits [13,26,27]. The activity of FoxP2-positive cells depended on an interaction of behavioral group and brain region (group*region: F_4 =

130.66, $p < 0.001$). Begging tadpoles had more active FoxP2-positive cells than aggressive and control tadpoles in the striatum (Str, aggression vs begging: $z = -3.144$, $p = 0.005$; begging vs control: $z = 2.517$, $p = 0.018$) and cerebellum (Cb, aggression vs begging: $z = -2.490$, $p = 0.019$; begging vs control: $z = 3.626$, $p < 0.001$). The number of active FoxP2-positive cells did not differ between aggressive and control animals in the striatum ($p = 0.175$) or cerebellum ($p = 0.920$). Aggressive tadpoles had more active FoxP2-positive cells than control tadpoles in the nucleus accumbens (NAcc, $z = 2.989$, $p = 0.008$), whereas activity of FoxP2-positive cells did not differ between begging and aggression ($p = 0.125$) or control ($p = 0.125$) contexts. There was a significant difference in the number of FoxP2-positive cells within these brain regions across groups, where aggressive tadpoles had fewer FoxP2 cells in the striatum (See Supplementary Materials).

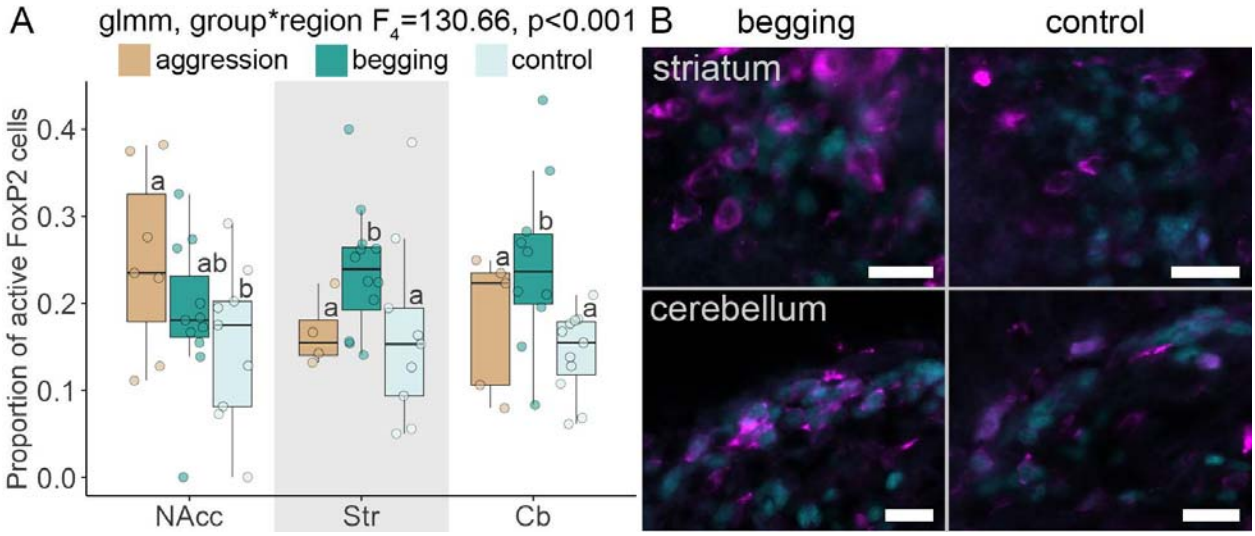

Figure 2. Activity of FoxP2 neurons increases in the striatum and cerebellum of begging tadpoles. (A) Proportion of active FoxP2-positive cells in aggressive (orange), begging (dark green) and control (light green) tadpoles are shown in boxplots with individual tadpoles displayed in dots. Within each brain region, groups not connected by the same letter are significantly different. **(B)** Representative micrographs of FoxP2 (green) and pS6 (pink) colocalization expression of begging (left) or control (right) tadpoles in the striatum and cerebellum. Scale bar is 10 microns. Abbreviations: Cb, cerebellum; NAcc, nucleus accumbens; Str, striatum.

Discussion

While there is variation in the types of signaling by infants, all require complex motor planning and execution coordinated by neural processes. Among other functions, the transcription factor FoxP2 plays a role in coordinating vocal communication in mammals and birds [14,17,20,26,43,44]. Our study expands the role of FoxP2 to social signaling in amphibians, suggesting a generalizable function of FoxP2 in social-motor coordination across terrestrial vertebrates.

The brain distribution of FoxP2 is conserved across vertebrates

FoxP2 is widespread throughout the amphibian brain, with a distribution pattern consistent with those found in other vertebrates (mammals: [45–47]; birds: [48]; fish: [49–51]). Across these taxa, there is a conserved pattern of expression in brain areas involved in motor output, sensory processing, and sensorimotor integration. In *R. imitator* tadpoles, brain regions that regulate motor output, including the basal ganglia and cerebellum, had many FoxP2-positive neurons. FoxP2 is expressed in the basal ganglia and cerebellum in avian vocal and non-vocal learners, crocodiles, and rodents, suggesting conserved expression in motor-related areas regardless of the ability to learn acoustic communication [45, 48]. We also noted FoxP2-positive cells in many sensory processing regions like the olfactory bulb (chemosensory), optic tectum (visual processing), and torus semicircularis (acoustic processing). In bats, species differences in FoxP2 expression in the olfactory bulb are associated with different feeding habits (frugivorous versus insectivorous) [52], suggesting that FoxP2 may influence olfactory processing. Given *R. imitator* tadpoles rely on smell to distinguish between caregiver stimuli [35], investigating FoxP2's role in sensory integration broadly may be a valuable future research direction. Overall, the distribution of FoxP2 in the amphibian brain suggests a largely conserved pattern across terrestrial vertebrates.

A general role for FoxP2 in social signaling

We found that activity of FoxP2-positive neurons was higher in the striatum and cerebellum of begging tadpoles compared to aggressive and control animals. Whether this pattern is directly relevant to begging requires functional manipulations in a brain region-specific manner. Regardless, our results suggest the role of FoxP2 may be generalizable beyond vocal communication to other types of social signaling.

The striatum is important for motor skills in many vertebrates [53] and has been linked to vocal communication in several taxa [54]. We found that FoxP2-positive cells in the striatum have increased activity specifically during tadpole begging, suggesting a function for this brain region in tadpole signaling. This is supported by many studies on the role of FoxP2 in the striatum of vocalizing birds and mammals. Deficits in songbird vocalizations are observed after FoxP2 knockdown in Area X, a striatal nucleus involved in song learning [20]. At a cellular level, FoxP2 has been implicated in structural plasticity, where FoxP2 modifications influence spiny dynamics of Area X neurons in zebra finches [55] and dendrite lengths of striatal neurons in mice [56]. In this same study, the variant of FoxP2 expressed in mice also impacted dopamine concentrations in the striatum and nucleus accumbens. Dopamine signaling is critical to tadpole begging behavior [35], and our results here suggest a potential role for FoxP2 in modulating dopamine signaling that should be investigated in the future. This general cellular dysregulation can be seen in mice with FoxP2 mutations, where the striatum is more active and motor-skill learning is disrupted due to abnormal temporal coordination of striatal firing [57]. Together, our work expands the potential role of FoxP2 in the striatum to motor signaling in amphibians, suggesting a conserved role for striatal FoxP2 in communication across tetrapod vertebrates.

The cerebellum is a highly conserved vertebrate brain region that coordinates voluntary movements and motor learning [58]. The cerebellum is also implicated in language [59], as there is higher overall cerebellar activity during language tasks in humans [60]. Mice expressing

FoxP2 with the R552H mutation (that leads to speech-language disorders in humans) have impaired ultrasonic vocalizations and poor dendritic development of FoxP2-positive cerebellar Purkinje cells [42]. A reduction of FoxP2 expression specifically in cerebellar Purkinje neurons leads to a reduction of ultrasonic vocalizations in mouse pups [61]. Moreover, expressing the wild type human FOXP2 in the cerebellum partially rescues ultrasonic vocalizations in mice with global expression FoxP2 with the R552H mutation [62]. To our knowledge, the role of FoxP2 in the cerebellum during vocal learning in songbirds is unknown, but cerebellar lesions impair song learning [63]. Our study, along with studies in neonatal mice, suggest that investigating the role of cerebellar FoxP2 during vocal signaling in songbirds would resolve whether the role of these neurons in coordinating motor signaling are generalizable across taxa.

Summary

We present evidence that FoxP2 has conserved brain expression patterns across vertebrates by filling in a critical taxonomic gap from amphibians. We also show that parent-directed signaling by tadpoles is correlated with activity of FoxP2-positive cells in the striatum and cerebellum. Overall, this work supports the idea that the FoxP2 transcription factor is part of a molecular toolkit important for motor-based signaling via striatal and cerebellar circuits across many animals.

Data Accessibility

All data are included in supplementary materials.

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Author contributions

Conceptualization: SCL and LAO
Methodology: SCL
Formal Analysis: SCL and LAO
Investigation: SCL, MGR, and JEM
Resources: LAO
Data Curation: SCL
Writing – original draft preparation: SCL and LAO
Writing – review and editing: JEM, MGR, and JMB
Visualization: SCL
Supervision: LAO, JMB
Project administration: LAO
Funding acquisition: LAO

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