Early-Life Dietary Restriction and Diet Type Affect Juvenile Brain Morphology in Spadefoot Toads (Spea bombifrons)

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Early-Life Dietary Restriction and Diet Type Affect Juvenile Brain Morphology in Spadefoot Toads (*Spea bombifrons*)

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Abstract: Across a breadth of animal taxa, early-life environmental variation has been demonstrated to have lasting effects on later-life traits, including brain morphology. Here, we use Plains Spadefoot Toads (*Spea bombifrons*) to evaluate how larval diet type and amount influence later-stage, juvenile brain size and the relative sizes of brain regions. We specifically investigate whether developmental plasticity in brain morphology mirrors previously documented interspecific variation with relation to nutritional restriction and carnivory. Our findings demonstrate, contrary to expectation, that exposure to dietary restriction during the larval stage causes an increase in relative juvenile brain size. However, consistent with our predictions, consuming a prey-based shrimp diet during the larval stage results in relatively larger juvenile telencephalons, an intraspecific response that parallels an interspecific pattern in frogs where more-carnivorous species possess relatively larger telencephalons. Our results demonstrate that early-life dietary restriction and early-life diet type can generate changes in juvenile brain size and morphology in ways that may influence later-life behaviors and fitness. Further, our study suggests that intraspecific and environmentally induced changes in brain morphology can mirror interspecific divergence in brain morphology, supporting a role for developmental plasticity in promoting evolutionary change.

Key words: Brain-sparing; Compensatory growth; Genetic accommodation; Mosaic brain evolution; Phenotypic plasticity; Polyphenism; Tadpole

Many studies have documented how external features of the environment—from environmental complexity to social structure—are associated with interspecific or interpopulational variation in brain morphology (Canady et al. 1984; Pravosudov et al. 2006; Pollen et al. 2007; Shumway 2008; Gonzalez-Voyer et al. 2009a; Roth and Pravosudov 2009; Snell-Rood et al. 2009; Park and Bell 2010; Snell-Rood and Wick 2013). Additionally, variation in brain morphology exists within species as the result of developmental responses to the environment (reveiwed in Gonda et al. 2013), and these changes can persist into later-life stages (e.g., Trokovic et al. 2011; Kotrschal et al. 2012a; Woodley et al. 2015). How environmentally induced, developmentally plastic changes in brain morphology are related to evolutionary divergence in brain morphology is less clear. That the evolutionary divergence of brain morphologies follows initially plastic responses, a process termed "genetic accommodation" (West-Eberhard 2003), is a compelling scenario given that brain morphology is both developmentally plastic (Triki et al. 2019) and can respond rapidly to selection (Fong et al. 2021; Triki et al. 2022). An understudied yet crucial step in understanding whether the evolution of brain size and morphology can occur via genetic accommodation is determining whether patterns that arise within species in response to an environmental factor parallel variation among lineages that have diverged, evolutionarily, in response to the same environmental factor (Levis and Pfennig 2016).

A common environmental stressor that developing organisms face is variation in resource availability and, consequently, nutritional restriction. Within a species, there are multiple mechanisms by which either nutritional restriction, or—if nutrition is subsequently obtained—the ensuing compensatory growth (Metcalfe and Monaghan 2001) might influence brain size. First, the Expensive Brain Framework posits that the costs of building a brain must be balanced by the costs of growth in other tissues, such that brain size is directly constrained by an energy budget (Aiello and Wheeler 1995; Isler and van Schaik 2009). Therefore, nutritional restriction might directly result in relatively small brain sizes through its diversion of energy toward overall body size (Gurney et al. 2003; Kuzawa et al. 2014). Second, compensatory growth might influence brain morphology indirectly through increased oxidative stress (Burraco et al. 2017) that impedes neuron survival (Saito et al. 2005). Third, nutritional restriction or compensatory growth might result in higher glucocorticoid levels (Ledón-Rettig et al. 2009) or lower insulin-like growth factors (Won and Borski 2013; Regan et al. 2020), both of which influence neuron survival and brain growth (Kim and Yoon 1998; D'Ercole and Ye 2008). Thus, a reasonable expectation would be that a temporary nutritional restriction or compensatory growth during early life results in relatively smaller brain sizes during later life. If such developmental plasticity directs the evolution of interspecific variation, we would also predict that species that often experience nutritional restriction possess smaller brains. In support of this scenario, comparative studies of frogs, butterflies, and primates have found that limited nutritional availability or quality is associated with smaller brain sizes among species (Van Woerden et al. 2010; Luo et al. 2017; Snell-Rood et al. 2020). However, it is

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unclear whether there is a link between the effects of nutritional restriction on brain size within species and general patterns of brain size among species.

In addition to nutritional restriction, a ubiquitous source of early-life environmental variation is resource type. Many developing organisms can adopt a diversity of diet types, where the acquisition of different resources requires distinct behaviors or morphologies (Futuyma and Moreno 1988). North American Spadefoot Toads of the genus *Spea* offer an ideal model to evaluate whether variation in early-life nutrition influences brain size and morphology because their larvae (i.e., tapdoles) can specialize on alternate and distinct diets: in addition to their ancestral diet of decaying plant and animal material (hereafter "detritus"; Bragg 1964), they are also capable of pursuing and consuming live macroscopic prey, including shrimp and other tadpoles (Ledón-Rettig and Pfennig 2011). Specialization on a live prey diet requires a behavioral shift, as these aquatic predators must pursue prey in three dimensions. Indeed, a recent study using *S. bombifrons* found that the brains of shrimp-fed larvae uniquely expressed a suite of genes enriched for those involved in spatial learning and memory (Ledón-Rettig 2021). These specific behavioral processes, and prey capture more generally, are mediated by the telencephalon across vertebrates (Broglio et al. 2010; O'Connell and Hofmann 2011; Oldfield et al. 2020). Consistent with the role of the telencephalon in prey capture, a phylogenetically controlled survey of several brain regions across 43 species of frogs found that more-carnivorous species had larger telencephalons than did more-omnivorous species (Liao et al. 2015). The frogs assessed in that survey are not closely related to Spadefoot Toads; however, if juvenile *Spea* exhibited relatively enlarged telencephalons in response to a carnivorous larval diet—paralleling variation in telencephalon size among species—this would suggest that some interspecific differences might be initiated through developmental plasticity, i.e., through genetic accommodation (Palmer 2012).

In this study, using the North American Plains Spadefoot Toad, *Spea bombifrons*, we made two predictions regarding plasticity in relative brain size and brain region size in response to dietary variation. We first hypothesized that a temporary or permanent larval dietary restriction would cause a reduction in juvenile brain size relative to overall body size because of energetic constraints or indirect effects related to the restriction. Second, we hypothesized that an early-life diet of shrimp would produce selective enlargement of the telencephalon, a brain region involved with prey capture. Contrary to our first hypothesis, we found that individuals who experienced a temporary or permanent dietary restriction during early life in fact have relatively larger overall brain sizes. Consistent with our second hypothesis, we found that individuals who consumed a prey-based diet in early life have relatively larger telencephalons. We discuss our results in the context of macroevolutionary patterns of brain morphology previously revealed in frogs.

Materials and Methods

Here we expanded on a previously conducted experiment (Ledón-Rettig and Lagon 2021). Using animals from Ledón-Rettig and Lagon 2021, we collected new data on brain morphometrics and final body size. Relevant aspects of the experimental design and assays from the previous study are provided below (see Breeding and Microcosm Set-up and Larval Dietary Treatment sections). New data and analyses (see Brain Collection and Morphometrics and Statistics Sections) are provided in full.

Breeding and Microcosm Set-up

Adult *S. bombifrons* were collected from Willcox, Arizona in the summer of 2018 and transported to Indiana University. The colony and all experiments described here were approved by the Bloomington Institutional Animal Care and Use Committee (IACUC Protocol no. 18-011-7). Adults were injected with Luteinizing Hormone Releasing Hormone (LHRH; GenScript RP11937), with females and males receiving 1 unit per gram and 0.5 unit per gram of mass, respectively. Following injection, pairs were left overnight to mate in a breeding container filled with aged and dechlorinated water. One clutch of eggs was chosen for the experiment. Using one family was not ideal, as the degree of developmental change in brain size can vary at a family level (Snell-Rood et al. 2009); caution should therefore be taken in generalizing our results. Approximately 48 h after eggs were laid, larvae hatched and were transferred to individual microcosms (18 × 11 × 14 cm) filled with 800 mL dechlorinated and aged water.

Larval Dietary Treatment

We varied larval diets by two types and three amounts, thereby generating six treatments: shrimp-fed normal; shrimp-fed and temporarily diet-restricted; shrimp-fed and permanently diet-restricted; detritus-fed normal; detritus-fed and temporarily diet-restricted; and detritus-fed and permanently diet-restricted. Two levels of diet restriction were used to distinguish potential carry-over effects resulting from compensatory growth from effects resulting from the initial restriction itself. Detritus was provided as ground fish food, which contains many elements found in *S. bombifrons*' natal ponds (e.g., algae, yeast, and animal protein). Shrimp were provided as live *Artemia*, which are similar to the shrimp that co-occur in *S. bombifrons*' natal ponds (Pomeroy 1981). The microcosms were randomized by treatment (with 33 replicates each) and distributed across racks.

Individuals in the normal treatment were fed an ad libitum amount of food; those in the temporarily restricted treatments received half the amount. The amount of food provided in each treatment was adjusted as the larvae grew, such that the individuals in the ad libitum group always had a little food left over by the next feeding. At 15 d, individuals in the temporarily restricted group were transitioned to an ad libitum diet while those in the ad libitum and permanently restricted groups were continued on their diets. Larvae remained on these dietary regimes until they metamorphosed; during this time, the water in the microcosms was changed twice a week to prevent fouling. As larvae underwent metamorphosis, defined as forearm emergence, they were placed in microcosms with sand on one side and a thin layer of water on the other to facilitate their transition. Once metamorphosis was complete, the entire bottom of the microcosm was covered in moist sand and the juveniles were provided a diet of crickets. At approximately 12 wk postmetamorphosis, animals were euthanized and their

brains were dissected and weighed. Final body sizes of individuals were obtained by weighing their formalin-fixed bodies (see below) and summing these values with the corresponding brain mass.

Brain Collection and Morphometrics

Brains were collected approximately 12 wk postmetamorphosis to ensure all brain remodeling that occurs during metamorphosis was complete (Denver et al. 1997). A 20% benzocaine gel was applied topically and individuals were euthanized by cervical dislocation. Gonado-mesonephros complexes and brains were then dissected and placed in separate tubes of RNAProtect (QIAGEN 1018087) for storage. The remaining carcasses were preserved in 10% buffered formalin until they were weighed at a later date. Dissections, photography, and measurements were all conducted in the order of the randomly assigned treatments; i.e., any potential drift in technique would occur across treatments, equally. Each brain sample was weighed, transferred to a dish filled with new RNAProtect, photographed using an OMAX A35180U3 microscope digital camera, returned to its tube, and held at –20°C for long-term storage. Dorsal, ventral, and lateral images were taken for brains. To reduce any measurement errors introduced by perspective bias, brains were flatly positioned so that both hemispheres were equally mirrored. Images of gonado-mesonephros were used to determine an individual's sex, and images of brains were used for morphometric analyses. Individuals whose sex could not be determined visually (approximately 10%) were assessed using a (quantitative polymerase chain reaction) analysis of gonado-mesonephros tissue (sensu Navarro-Martín et al. 2012; see Supplemental Materials, available online). Primers are provided in Supplemental Table S1 in the Supplemental Materials. Three individuals who remained ambiguous were removed from the analyses. Sex, however, did not have a significant effect on juvenile growth, whole brain size, or relative brain region sizes (Supplemental Tables S2–S4, available online), and will not be discussed further.

One researcher who was blind to treatment type performed measurements of height, length, and width for the following five brain regions: telencephalon, diencephalon (excluding the hypothalamus), optic tectum, cerebellum, and hypothalamus. Measurements (Supplemental Fig. S1, available online) were taken with ImageJ (Schneider et al. 2012). Although we specifically hypothesized that there would be diet-dependent plasticity in telencephalon volumes, we measured other regions to determine whether there were any potential trade-offs arising from energetic constraints. Height and length measurements for all brain regions were taken from the lateral view, while width measurements for all but the hypothalamus were taken from the dorsal view. Width measurements for the hypothalamus were taken from the ventral view. Brain regional measurements were then used to calculate regional volumes, as reported in Kotrschal et al. (2012a), albeit only one lateral view was used to measure one side of the telencephalon and optic tectum. Regional volumes were determined using the ellipsoid equation:

$$V = \frac{\pi}{6}(L \times W \times H)$$

Three brains were damaged during dissection, resulting in fractured regions (e.g., partial telencephalon or absent cerebellum). Brains with incomplete regions that could not be measured for length, width, and height were removed from analysis. The final sample size for harvested brains was 172, or 25–32 individuals per treatment. A survival analysis performed in (Ledón-Rettig and Lagon 2021) found that survival did not vary across treatments.

To determine the repeatability of our measurements, brains from 14 individuals were selected (evenly from shrimp and detritus diets), rephotographed with two images per view, and remeasured. Repeatability for the volumes of most structures was high ($r = 0.81$–0.90; all $P < 0.001$). The repeatabilities of diencephalon and hypothalamus volumes were less so ($r = 0.60$ and 0.71; $P = 0.02$ and 0.005, respectively), however, they are not featured in our interpretation of the results.

Statistics

All models here and below were executed using the base stats package in R v4.2.2 (R Core Team 2022) and plots were built with the package ggplot2 v3.4.0 (Wickham 2016). We first determined how juveniles from different treatments varied in size at the time that brains were dissected. We used whole body mass at 12 wk as the response variable in an ANOVA that had diet type, diet amount, sex, and all their interactions as predictor variables. For this model and those described below, we corrected for multiple hypothesis testing within models (i.e., for each predictor and interaction between predictors), using a sequential Bonferroni correction (i.e., Holm's correction; Holm 1979) on all the *P*-values, as suggested in Forstmeier and Schielzeth (2011). For post hoc comparisons of predictor variables that had multiple levels (i.e., diet amount), we used estimated marginal means (R package emmeans; Lenth 2021) with Benjamini-Hochberg corrections for multiple comparisons. We calculated partial eta-squared values (η_p^2) as measures of effect sizes.

To determine how relative brain sizes varied over treatments, whole juvenile brain mass was used as the response variable in an ANOVA that had diet type, diet amount, juvenile mass at 12 wk, sex, and all their interactions as predictor variables. The mass at the time of dissection was included to control for the allometric relationship between brain and body sizes (Packard and Boardman 1999; Striedter 2005; Nakagawa et al. 2017).

To determine whether early-life dietary variation influenced the relative sizes of specific brain regions (telencephalon, diencephalon, optic tectum, hypothalamus, and cerebellum), brain region volumes were used as response variables in ANOVAs that had diet type, diet amount, whole brain mass at 12 wk, sex, and all their interactions as predictor variables. The telencephalon and diencephalon volumes met the conditions of normality as determined by a Shapiro–Wilk test, but the hypothalamus, cerebellum, and optic tectum volumes were natural log-transformed to improve normality. Corrections for multiple hypothesis testing and post hoc comparisons were conducted as outlined above. Relationships among brain region sizes were performed and visualized using the corrplot (Wei et al. 2017) and Hmisc (Frank and Harrell 2021) packages. Data are available on Dryad (https://dx.doi.org/10.5061/dryad.p5hqbzksz).

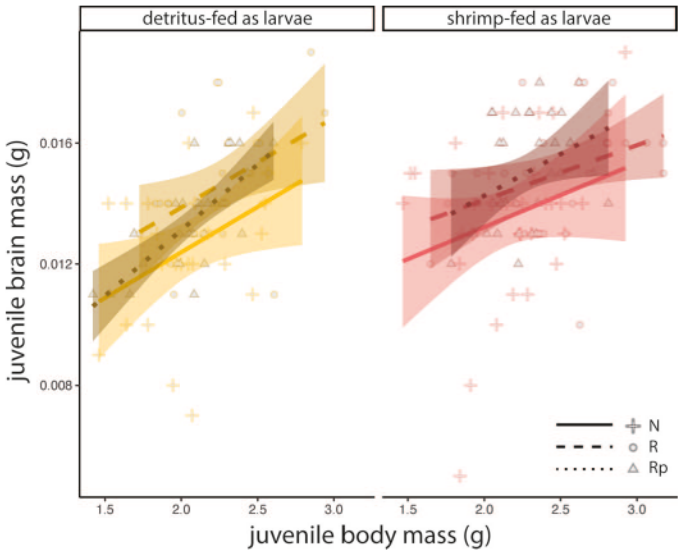

FIG. 1.—Early-life dietary restriction and diet type affect juvenile brain sizes. After correcting for body size, both temporary and permanent early-life dietary restriction (both $P = 0.008$ following post hoc correction for multiple tests) and a shrimp diet ($P_{adj} = 0.03$) increased relative brain sizes. Diet amounts are normal (N), temporarily restricted (R), and permanently restricted (Rp).

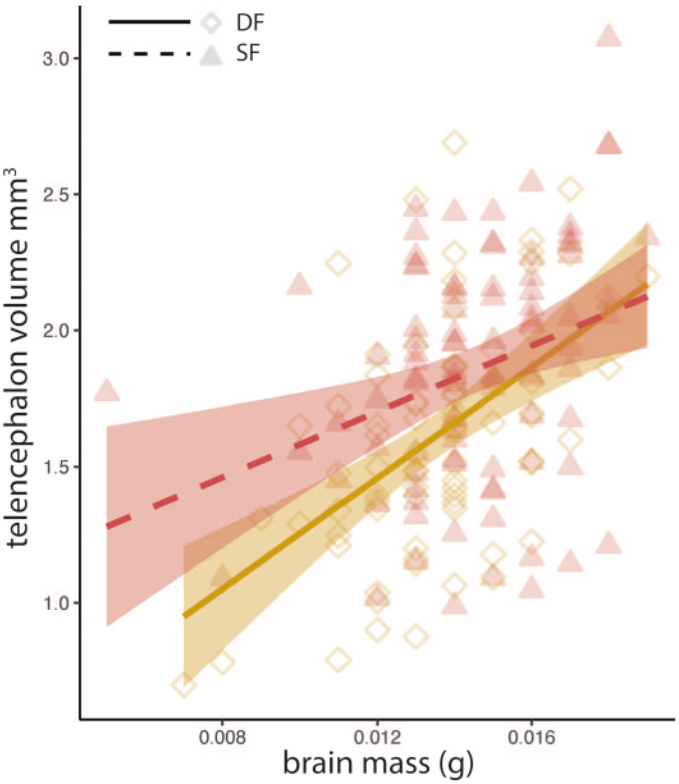

FIG. 2.—Juveniles that consumed shrimp as larvae have larger telencephalons. After correcting for brain size, juveniles that had been fed shrimp as larvae had larger telencephalons than those that had been fed detritus ($P = 0.001$). Shaded areas around lines reflect 0.95 confidence intervals. Larval diet types are detritus-fed (DF) and shrimp-fed (SF).

RESULTS

With respect to juvenile mass at 12 wk postmetamorphosis, those who had consumed shrimp as larvae were significantly larger (η_p^2: 0.07, $F_{1,160} = 11.20$, $P_{adj} = 0.006$). Larval diet amount also had a significant effect on juvenile mass (η_p^2: 0.11, $F_{2,160} = 9.97$, $P_{adj} = 0.001$), such that individuals who had experienced a temporary nutritional restriction as larvae were larger than those who experienced a permanent nutritional restriction ($P_{adj} = 0.004$) and those who experienced an ample diet ($P_{adj} < 0.001$); the latter two groups did not significantly differ from each other. Growth curves are presented in Supplemental Figure S2 and the full model is presented in Supplemental Table S2. Data on time to metamorphosis and growth rates are as reported in Ledón-Rettig and Lagon 2021; in brief, juveniles that had experienced diet restriction as larvae but were then transitioned to a normal diet were significantly larger than juveniles that had been fed a consistently normal or restricted diet. The enhanced size at metamorphosis of individuals that had experienced a temporary nutritional restriction was due to both a longer larval growth period and an enhanced growth rate.

Even after correcting for body size, larval diet amount (η_p^2: 0.06, $F_{2,148} = 10.81$, $P_{adj} = 0.001$) and type (η_p^2: 0.13, $F_{1,148} = 9.64$, $P_{adj} = 0.03$) influenced the sizes of whole juvenile brains, with those that consumed shrimp as larvae having larger brains (Fig. 1; Supplemental Table S3). A post hoc analysis revealed that individuals that experienced a temporarily or permanently restricted diet as larvae had larger brains as juveniles than those that experienced a normal diet ($P_{adj} = 0.008$); these two restricted groups did not, however, significantly differ from each other in brain size.

When considering the relative sizes of specific brain regions, a shrimp larval diet resulted in significantly larger juvenile telencephalons (η_p^2: 0.10, $F_{1,147} = 16.28$, $P_{adj} =$ 0.001; Fig. 2; Supplemental Table S4). Additionally, a shrimp larval diet tended to produce larger juvenile optic tecta (η_p^2: 0.05, $F_{1,148} = 8.02$, $P_{adj} = 0.07$; Supplemental Table S5), but this effect was not significant. None of the other juvenile brain regions were significantly influenced by larval diet type or amount. A comparison of correlations among brain regions did not reveal a negative correlation between the telencephalon and any other brain region (Supplemental Fig. S3), suggesting that diet-induced changes in telencephalon volume can occur independently of other brain regions (Barton and Harvey 2000; Gonzalez-Voyer et al. 2009b).

DISCUSSION

Our study has found that an early-life nutritional restriction increases relative juvenile brain size. The increase in relative brain size was common to individuals who experienced a temporary or permanent restriction, suggesting that the increase is associated with the early-life restriction itself and not subsequent compensatory growth. These results are inconsistent with our initial proposal that an early-life nutritional restriction might divert energy from brain development into overall growth. Possibly, during this window of restriction, resources that could be allocated to body growth were preferentially diverted to brain development, i.e., brain-sparing (Ravelli et al. 1998; Barker 2004; Lanet and Maurange 2014). Yet, the brain-sparing hypothesis predicts that individuals that experience an early-life nutritional restriction will demonstrate an improved brain-

to-body ratio rather than larger overall brains when compared to individuals that have access to ample resources (Rock et al. 2021), as observed in our study. Thus, our results may indicate that during this developmental window, a slower overall growth rate—imposed by a nutritional restriction—in fact promoted brain development, permanently recalibrating relative brain sizes.

Examples where delayed body growth enhances brain growth have been observed in other taxa. In fish, a study of Coho Salmon (*Oncorhynchus kisutch*) that were transgenically modified to overexpress growth hormone (GH) revealed that these faster-growing salmon had smaller brains than their control counterparts; this effect was obviated by restricting the diets of the transgenic salmon, suggesting that growth rate per se was responsible for the smaller brain sizes (Devlin et al. 2012; Kotrschal et al. 2012b). Another study comparing runt (i.e., smaller) pigs and their littermates revealed similar brain sizes, and relatively larger brains in runts once body size was accounted for (Ritacco et al. 1997). How nutritional restriction might promote brain growth is unclear. Possibly, the brains of individuals in this study who experienced nutritional restriction are built with a lower neuronal cell density, as these types of cells are most costly (Herculano-Houzel 2011, 2012). For instance, despite having brains that are proportional to their body sizes, Brown Bears (*Ursus arctos*) have substantially fewer neurons in its cerebral cortex, possibly due to the metabolic costs of maintaining a large body size (Jardim-Messeder et al. 2017). However, modifying the density of neuronal cells within brains would not entirely explain how animals that experienced nutritional restriction possessed overall larger brains. Thus, the connection between attenuated body growth and enhanced brain growth warrants further investigation.

A previous study using Leopard Frogs (*Lithobates pipiens*) also manipulated larval food amount in outdoor mesocosms and measured brain sizes at metamorphosis, but found no effect of a restricted diet on brain size (Woodley et al. 2015). The discrepancy between our findings and the results of the Leopard Frogs study might be due to variation in developmental responses to nutrition among species. Alternatively, we propose that the overall growth rate in our study was much greater than in the Leopard Frogs study, revealing variation in the effects of growth rate on brain size that might not otherwise be seen. Specifically, Woodley and colleagues reported that the density of larvae in each of their mesocosms was high and that growth rates were low; indeed, the masses and developmental speeds of individuals in their control and food-restricted treatments were statistically similar. In contrast, we raised our larvae singly, such that growth rates were unabated by competition. Growth under high densities is likely typical for *S. bombifrons* in nature; however, variation in growth rate is likely also substantial, as individuals experience consistently low and high growth rates as well as growth rates that are initially low (due to competition) and later, high (after competition is reduced by predation; Wilbur 1987).

With respect to diet type, juveniles derived from larvae that had consumed shrimp also had larger overall brain size, which is easier to reconcile with the Expensive Brain Framework (Aiello and Wheeler 1995; Isler and van Schaik 2009): the shrimp diet is higher in protein and fat, which would allow for the expansion of the energetically expensive brain without requiring reallocation from other tissues. Indeed, the relationship between higher-quality diets and relative brain size has been demonstrated among taxa (Gittleman 1986; Dunbar and Shultz 2007; Swanson et al. 2012; DeCasien et al. 2017; Snell-Rood et al. 2020; but see Gonzalez-Voyer et al. 2009b, and Allen and Kay 2012), although there was no association between a more-carnivorous diet and brain size in the survey of frogs (Liao et al. 2015). One important consideration of our study is that, although larvae were fed different quality diets, all juveniles were fed the same diet postmetamorphosis. Thus, regardless of how permissive the high-quality shrimp resource is for larval brain growth, juveniles derived from shrimp-fed larvae have to pay a proportionally higher cost for brain maintenance in their terrestrial life. Whether large postmetamorphic brains come at a cost to fitness because they are energetically expensive, or whether they produce any fitness variation through their effects on cognition and behaviors, should be empirically addressed in future studies.

Additionally, we found that—within whole brains—a larval diet of shrimp promoted relatively larger juvenile telencephalons. Given that frog species that are more carnivorous possess larger telencephalons (Liao et al. 2015), our findings are consistent with a scenario of genetic accommodation, whereby a developmentally plastic response to a particular environmental variable mimics an evolutionary response to the same variable. However, some questions still need to be addressed to provide resounding evidence that developmental plasticity plays a role in brain evolution in Spadefoot Toads or other frogs. First, only one family was used in this study, so it is not clear whether these results are characteristic of all *S. bombifrons* or whether families vary in the degree of their brain plasticity in response to larval diet type. Indeed, genetic variation for brain plasticity during development has been observed in other taxa (Snell-Rood et al. 2009). Further, it is not clear whether larger telencephalon sizes, modified as the result of an environmental pressure experienced by larvae, would still be adaptive in the juvenile stage. Many animals vary in their resource use and ecology throughout ontogeny, such that trait modifications wrought through developmental plasticity may have stage-specific effects on fitness. If the developmental response of a trait to the environment improves fitness across life stages, selection may favor alleles that make the trait more responsive to the environment (Moore and Martin 2019). In contrast, if the developmental response of a trait to the environment has contrasting effects on fitness across life stages, also called ontogenetic conflict (Calsbeek and Goedert 2017; Moore and Martin 2018), selection may dampen the environmental sensitivity of the trait. Future studies might pursue whether the observed plastic differences in brain sizes and relative brain region are, in fact, associated with ecologically relevant variation in behaviors, whether these behaviors influence juvenile fitness, and whether the fitness effects promote or constrain the process of genetic accommodation.

Conclusions

Despite the assumption that behavioral plasticity plays a critical role in genetic accommodation (Baldwin 1896; Mayr 1963; Price et al. 2003), there is still a deficit of studies

addressing the evolution of behaviors, themselves, via genetic accommodation (Levis and Pfennig 2020). Demonstrating that brain morphology can evolve via genetic accommodation would suggest that ancestral plasticity in behavioral states, like any other morphological or physiological trait, can evolve through this process (Renn and Schumer 2013). Indeed, although brain morphology masks other predictors of behavior such the connectedness of neurons and expression of neurotransmitters or receptors (Goodson et al. 2012; van den Heuvel et al. 2016; Jardim-Messeder et al. 2017), relative brain size and the relative sizes of brain regions can still predict cognitive abilities and behavioral traits (Timmermans et al. 2000; Reader and Laland 2002; Sol et al. 2005a,b, 2008; Ratcliffe et al. 2006; Mehlhorn et al. 2010; Triki et al. 2022). Our results corroborate earlier studies demonstrating that brain and brain region sizes are developmentally plastic and even mirror interspecific variation in morphologies, suggesting that plasticity may play a role in brain and behavioral evolution.

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Supplemental Material

Supplemental material associated with this article can be found online at https://doi.org/10.1655/Herpetologica-D-22-00040.S1

Literature Cited

Aiello, L.C., and P. Wheeler. 1995. The expensive-tissue hypothesis: The brain and the digestive system in human and primate evolution. Current Anthropology 36:199–221. DOI: https://dx.doi.org/10.1086/204350

Allen, K.L., and R.F. Kay. 2012. Dietary quality and encephalization in platyrrhine primates. Proceedings of the Royal Society B: Biological Sciences 279:715–721. DOI: https://dx.doi.org/10.1098/rspb.2011.1311

Baldwin, J.M. 1896. A new factor in evolution. American Naturalist 30:441–451.

Barker, D.J.P. 2004. The developmental origins of well-being. Philosophical Transactions of the Royal Society B: Biological Sciences 359:1359–1366. DOI: https://dx.doi.org/10.1098/rstb.2004.1518.

Barton, R.A., and P.H. Harvey. 2000. Mosaic evolution of brain structure in mammals. Nature 405:1055–1058. DOI: https://dx.doi.org/10.1038/35016580

Bragg, A.N. 1964. Further study of predation and cannibalism in spadefoot tadpoles. Herpetologica 20:17–24.

Broglio, C., F. Rodríguez, A. Gómez, J.L. Arias, and C. Salas. 2010. Selective involvement of the goldfish lateral pallium in spatial memory. Behavioural Brain Research 210:191–201. DOI: https://dx.doi.org/10.1016/j.bbr.2010.02.031

Burraco, P., C. Díaz-Paniagua, and I. Gomez-Mestre. 2017. Different effects of accelerated development and enhanced growth on oxidative stress and telomere shortening in amphibian larvae. Scientific Reports 7:1–11. DOI: https://dx.doi.org/10.1038/s41598-017-07201-z

Calsbeek, R., and D. Goedert. 2017. Performance tradeoffs, ontogenetic conflict, and multisport athletes: How is an ironman triathlete like a frog? Integrative and Comparative Biology 57:207–216. DOI: https://dx.doi.org/10.1093/icb/icx014

Canady, R.A., D.E. Kroodsma, and F. Nottebohm. 1984. Population differences in complexity of a learned skill are correlated with the brain space involved. Proceedings of the National Academy of Sciences of the United States of America 81:6232–6234. DOI: https://dx.doi.org/10.1073/pnas.81.19.6232

D'Ercole, A.J., and P. Ye. 2008. Minireview: Expanding the mind: Insulin-like growth factor I and brain development. Endocrinology 149:5958–5962. DOI: https://dx.doi.org/10.1210/en.2008-0920

DeCasien, A.R., S.A. Williams, and J.P. Higham. 2017. Primate brain size is predicted by diet but not sociality. Nature Ecology and Evolution 1:1–7. DOI: https://dx.doi.org/10.1038/s41559-017-0112

Denver, R.J., S. Pavgi, and Y.B. Shi. 1997. Thyroid hormone-dependent gene expression program for *Xenopus* neural development. Journal of Biological Chemistry 272:8179–8188. DOI: https://dx.doi.org/10.1074/jbc.272.13.8179

Devlin, R.H., W.E. Vandersteen, M. Uh, and E.D. Stevens. 2012. Genetically modified growth affects allometry of eye and brain in salmonids. Canadian Journal of Zoology 90:193–202. DOI: https://dx.doi.org/10.1139/Z11-126

Dunbar, R.I.M., and S. Shultz. 2007. Understanding primate brain evolution. Philosophical Transactions of the Royal Society B: Biological Sciences 361:649–658. DOI: https://dx.doi.org/10.1098/rstb.2006.2001

Fong, S., B. Rogell, M. Amcoff, A. Kotrschal, W. van der Bijl, S.D. Buechel, and N. Kolm. 2021. Rapid mosaic brain evolution under artificial selection for relative telencephalon size in the guppy (*Poecilia reticulata*). Science Advances 7:eabj4314. DOI: https://dx.doi.org/10.1126/sciadv.abj4314

Forstmeier, W., and H. Schielzeth. 2011. Cryptic multiple hypotheses testing in linear models: Overestimated effect sizes and the winner's curse. Behavioral Ecology and Sociobiology 65:47–55. DOI: https://dx.doi.org/10.1007/s00265-010-1038-5

Frank, M., and E. Harrell. 2021. R Package Hmisc: Harrell Miscellaneous. Available at https://CRAN.R-project.org/package=Hmisc. R Foundation for Statistical Computing, Austria.

Futuyma, D.J., and G. Moreno. 1988. The evolution of ecological specialization. Annual Review of Ecology, Evolution, and Systematics 19:207–233. DOI: https://dx.doi.org/10.1146/annurev.es.19.110188.001231

Gittleman, J.L. 1986. Carnivore brain size, behavioral ecology, and phylogeny. Journal of Mammalogy 67:23–26. DOI: https://dx.doi.org/10.2307/1380998

Gonda, A., G. Herczeg, and J. Merilä. 2013. Evolutionary ecology of intraspecific brain size variation: A review. Ecology and Evolution 3:2751–2764. DOI: https://dx.doi.org/10.1002/ece3.627

Gonzalez-Voyer, A., S. Winberg, and N. Kolm. 2009a. Social fishes and single mothers: Brain evolution in African cichlids. Proceedings of the Royal Society B: Biological Sciences 276:161–167. DOI: https://dx.doi.org/10.1098/rspb.2008.0979

Gonzalez-Voyer, A., S. Winberg, and N. Kolm. 2009b. Brain structure evolution in a basal vertebrate clade: Evidence from phylogenetic comparative analysis of cichlid fishes BMC Evolutionary Biology 9:1–12. DOI: https://dx.doi.org/10.1186/1471-2148-9-238

Goodson, J.L., A.M. Kelly, and M.A. Kingsbury. 2012. Evolving nonapeptide mechanisms of gregariousness and social diversity in birds. Hormones and Behavior 61:239–250. DOI: https://dx.doi.org/10.1016/j.yhbeh.2012.01.005

Gurney, W.S.C., W. Jones, A.R. Veitch, and R.M. Nisbet. 2003. Resource allocation, hyperphagia, and compensatory growth in juveniles. Ecology 84:2777–2787. DOI: https://dx.doi.org/10.1890/02-0536

Herculano-Houzel, S. 2011. Scaling of brain metabolism with a fixed energy budget per neuron: Implications for neuronal activity, plasticity and evolution. PLoS One 6:e17514. DOI: https://dx.doi.org/10.1371/journal.pone.0017514

Herculano-Houzel, S. 2012. The remarkable, yet not extraordinary, human brain as a scaled-up primate brain and its associated cost. Proceedings of the National Academy of Sciences of the United States of America 109:10661–10668. DOI: https://dx.doi.org/10.1073/pnas.1201895109

Holm, S. 1979. A simple sequentially rejective multiple test procedure. Scandinavian Journal of Statistics 6:65–70.

Isler, K., and C.P. van Schaik. 2009. The Expensive Brain: A framework for explaining evolutionary changes in brain size. Journal of Human Evolution 57:392–400. DOI: https://dx.doi.org/10.1016/j.jhevol.2009.04.009

Jardim-Messeder, D., K. S. NoctorLambert, . . . S. Herculano-Houzel. 2017. Dogs have the most neurons, though not the largest brain: Trade-off between body mass and number of neurons in the cerebral cortex of large carnivoran species. Frontiers in Neuroanatomy 11:118. DOI: https://dx.doi.org/10.3389/fnana.2017.00118

Kim, J., and K.S. Yoon. 1998. Stress: Metaplastic effects in the hippocampus. Trends in Neurosciences 21:505–509. DOI: https://dx.doi.org/10.1016/S0166-2236(98)01322-8

Kotrschal, A., B. Rogell, A.A. Maklakov, and N. Kolm. 2012a. Sex-specific plasticity in brain morphology depends on social environment of the guppy, *Poecilia reticulata*. Behavioral Ecology and Sociobiology 66:1485–1492. DOI: https://dx.doi.org/10.1007/s00265-012-1403-7

Kotrschal, A., L.F. Sundström, D. Brelin, R.H. Devlin, and N. Kolm. 2012b. Inside the heads of David and Goliath: Environmental effects on brain morphology among wild and growth-enhanced coho salmon *Oncorhynchus kisutch*. Journal of Fish Biology 81:987–1002. DOI: https://dx.doi.org/10.1111/j.1095-8649.2012.03348.x

Kuzawa, C.W., H.T. L.I. GrossmanChugani, … N. Lange. 2014. Metabolic costs and evolutionary implications of human brain development. Proceedings of the National Academy of Sciences of the United States of America 111:13010–13015. DOI: https://dx.doi.org/10.1073/pnas.1323099111

Lanet, E., and C. Maurange. 2014. Building a brain under nutritional restriction: Insights on sparing and plasticity from *Drosophila* studies. Frontiers in Physiology 5:117. DOI: https://dx.doi.org/10.3389/fphys.2014.00117

Ledón-Rettig, C.C. 2021. Novel brain gene-expression patterns are associated with a novel predaceous behaviour in tadpoles. Proceedings of the Royal Society B: Biological Sciences 288:20210079. DOI: https://dx.doi.org/10.1098/rspb.2021.0079

Ledón-Rettig, C.C., and S.R. Lagon. 2021. A novel larval diet interacts with nutritional stress to modify juvenile behaviors and glucocorticoid responses. Ecology and Evolution 11:10880–10891. DOI: https://dx.doi.org/10.1002/ece3.7860

Ledón-Rettig, C.C., and D.W. Pfennig. 2011. Emerging model systems in eco-evo-devo: The environmentally responsive spadefoot toad. Evolution and Development 13:391–400. DOI: https://dx.doi.org/10.1111/j.1525-142X.2011.00494.x

Ledón-Rettig, C.C., D.W. Pfennig, and E.J. Crespi. 2009. Stress hormones and the fitness consequences associated with the transition to a novel diet in larval amphibians. Journal of Experimental Biology 212:3743–3750. DOI: https://dx.doi.org/10.1242/jeb.034066

Lenth, R. V. 2021. emmeans: Estimated Marginal Means, aka Least-Square Means, R package Version 1.6.3. Available at https://cran.r-project.org/web/packages/emmeans/index.html. R Foundation for Statistical Computing, Austria.

Levis, N.A., and D.W. Pfennig. 2016. Evaluating "plasticity-first" evolution in nature: Key criteria and empirical approaches. Trends in Ecology and Evolution 31:562–574. DOI: https://dx.doi.org/10.1016/j.tree.2016.03.012

Levis, N.A., and D.W. Pfennig. 2020. Plasticity-led evolution: A survey of developmental mechanisms and empirical tests. Evolution and Development 22:71–87. DOI: https://dx.doi.org/10.1111/ede.12309

Liao, W.B., S.L. Lou, Y. Zeng, and J. Merilä. 2015. Evolution of anuran brains: Disentangling ecological and phylogenetic sources of variation. Journal of Evolutionary Biology 28:1986–1996. DOI: https://dx.doi.org/10.1111/jeb.12714

Luo, Y., M.J. Zhong, Y. Huang, F. Li, W.B. Liao, and A. Kotrschal. 2017. Seasonality and brain size are negatively associated in frogs: Evidence for the expensive brain framework. Scientific Reports 7:1–9. DOI: https://dx.doi.org/10.1038/s41598-017-16921-1

Mayr, E. 1963. Animal Species and Evolution. Harvard Universty Press, USA.

Mehlhorn, J., G.R. Hunt, R.D. Gray, G. Rehkämper, and O. Güntürkün. 2010. Tool-making New Caledonian crows have large associative brain areas. Brain, Behavior and Evolution 75:63–70. DOI: https://dx.doi.org/10.1159/000295151

Metcalfe, N.B., and P. Monaghan. 2001. Compensation for a bad start: Grow now, pay later? Trends in Ecology and Evolution 16:254–260. DOI: https://dx.doi.org/10.1016/S0169-5347(01)02124-3

Moore, M.P., and R.A. Martin. 2018. Trade-offs between larval survival and adult ornament development depend on predator regime in a territorial dragonfly. Oecologia 188:97–106. DOI: https://dx.doi.org/10.1007/s00442-018-4171-x

Moore, M.P., and R.A. Martin. 2019. On the evolution of carry-over effects. Journal of Animal Ecology 88:1832–1844. DOI: https://dx.doi.org/10.1111/1365-2656.13081

Nakagawa, S., F. Kar, R.E. O'Dea, J.L. Pick, and M. Lagisz. 2017. Divide and conquer? Size adjustment with allometry and intermediate outcomes. BMC Biology 15:1–6. DOI: https://dx.doi.org/10.1186/s12915-017-0448-5

Navarro-Martín, L., Y.M. Velasco-Santamaría, P. Duarte-Guterman, C. Robertson, C. Lanctôt, B. Pauli, and V.L. Trudeau. 2012. Sexing frogs by real-time PCR: Using aromatase (cyp19) as an early ovarian differentiation marker. Sexual Development 6:303–315. DOI: https://dx.doi.org/10.1159/000343783

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

Oldfield, C.S., I. M. ChavezGrossrubatscher, … E.Y. Isacoff. 2020. Experience, circuit dynamics and forebrain recruitment in larval zebrafish prey capture. Elife 9. DOI: https://dx.doi.org/10.7554/ELIFE.56619

Packard, G.C., and T.J. Boardman. 1999. The use of percentages and size-specific indices to normalize physiological data for variation in body size: Wasted time, wasted effort? Comparative Biochemistry and Physiology: Part A, Molecular & Integrative Physiology 122:37–44. DOI: https://dx.doi.org/10.1016/S1095-6433(98)10170-8

Palmer, A.R. 2012. Developmental plasticity and the origin of novel forms: Unveiling cryptic genetic variation via "use and disuse." Journal of Experimental Zoology Part B: Molecular and Developmental Evolution 318:466–479. DOI: https://dx.doi.org/10.1002/jez.b.21447

Park, P.J., and M.A. Bell. 2010. Variation of telencephalon morphology of the threespine stickleback (*Gasterosteus aculeatus*) in relation to inferred ecology. Journal of Evolutionary Biology 23:1261–1277. DOI: https://dx.doi.org/10.1111/j.1420-9101.2010.01987.x

Pollen, A.A., A.P. Dobberfuhl, J. Scace, M.M. Igulu, S.C.P. Renn, C.A. Shumway, and H.A. Hofmann. 2007. Environmental complexity and social organization sculpt the brain in Lake Tanganyikan cichlid fish. Brain, Behavior and Evolution 70:21–39. DOI: https://dx.doi.org/10.1159/000101067

Pomeroy, L.V. 1981. Developmental Polymorphism in the Tadpoles of the Spadefoot Toad *Scaphiopus multiplicatus*. Ph.D. dissertation, University of California, Riverside, USA.

Pravosudov, V.V., A.S. Kitaysky, and A. Omanska. 2006. The relationship between migratory behaviour, memory and the hippocampus: An intraspecific comparison. Proceedings of the Royal Society B: Biological Sciences 273:2641–2649. DOI: https://dx.doi.org/10.1098/rspb.2006.3624

Price, T.D., A. Qvarnström, and D.E. Irwin. 2003. The role of phenotypic plasticity in driving genetic evolution. Proceedings of the Royal Society B: Biological Sciences 270:1433–1440. DOI: https://dx.doi.org/10.1098/rspb.2003.2372

Ratcliffe, J.M., M.B. Fenton, and S.J. Shettleworth. 2006. Behavioral flexibility positively correlated with relative brain volume in predatory bats. Brain, Behavior and Evolution 67:165–176. DOI: https://dx.doi.org/10.1159/000090980

Ravelli, A.C.J., J.H.P. Van Der Meulen, R.P.J. Michels, C. Osmond, D.J.P. Barker, C.N. Hales, and O.P. Bleker. 1998. Glucose tolerance in adults after prenatal exposure to famine. Lancet 351:173–177. DOI: https://dx.doi.org/10.1016/S0140-6736(97)07244-9

R Core Team. 2022. R: A Language and environment for statistical computing, version 4.2.2. Available at https://www.R-project.org/. R Foundation for Statistical Computing, Austria.

Reader, S.M., and K.N. Laland. 2002. Social intelligence, innovation, and enhanced brain size in primates. Proceedings of the National Academy of Sciences of the United States of America 99:4436–4441. DOI: https://dx.doi.org/10.1073/pnas.062041299

Regan, J.C., H. Froy, C.A. Walling, J.P. Moatt, and D.H. Nussey. 2020. Dietary restriction and insulin-like signalling pathways as adaptive plasticity: A synthesis and re-evaluation. Functional Ecology 34:107–128. DOI: https://dx.doi.org/10.1111/1365-2435.13418

Renn, S.C.P., and M.E. Schumer. 2013. Genetic accommodation and behavioural evolution: Insights from genomic studies. Animal Behaviour 85:1012–1022. DOI: https://dx.doi.org/10.1016/j.anbehav.2013.02.012

Ritacco, G., S. V. Radecki, and P.A. Schoknecht. 1997. Compensatory growth in runt pigs is not mediated by insulin-like growth factor I. Journal of Animal Science 75:1237–1243. DOI: https://dx.doi.org/10.2527/1997.7551237x

Rock, C.R., T.A. White, B.R. Piscopo, A.E. Sutherland, S.L. Miller, E.J. Camm, and B.J. Allison. 2021. Cardiovascular and cerebrovascular implications of growth restriction: Mechanisms and potential treatments. International Journal of Molecular Sciences 22:7555. DOI: https://dx.doi.org/10.3390/ijms22147555

Roth, T.C., and V. V. Pravosudov. 2009. Hippocampal volumes and neuron numbers increase along a gradient of environmental harshness: A large-scale comparison. Proceedings of the Royal Society B: Biological Sciences 276:401–405. DOI: https://dx.doi.org/10.1098/rspb.2008.1184

Saito, A., C.M. P. NarasimhanMaier, … P.H. Chan. 2005. Oxidative stress and neuronal death/survival signaling in cerebral ischemia. Molecular

Neurobiology 31:105–116. DOI: https://dx.doi.org/10.1385/MN:31:1-3:105
Schneider, C.A., W.S. Rasband, and K.W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. Nature Methods 9:671–675. DOI: https://dx.doi.org/10.1038/nmeth.2089
Shumway, C.A. 2008. Habitat complexity, brain, and behavior. Brain, Behavior and Evolution 72:123–134. DOI: https://dx.doi.org/10.1159/000151472
Snell-Rood, E.C., and N. Wick. 2013. Anthropogenic environments exert variable selection on cranial capacity in mammals. Proceedings of the Royal Society B: Biological Sciences 280:20131384. DOI: https://dx.doi.org/10.1098/rspb.2013.1384
Snell-Rood, E.C., D.R. Papaj, and W. Gronenberg. 2009. Brain size: A global or induced cost of learning? Brain, Behavior and Evolution 73:111–128. DOI: https://dx.doi.org/10.1159/000213647
Snell-Rood, E.C., E.M. A. EspesetSwanson, … E.T. Borer. 2020. Nutritional constraints on brain evolution: Sodium and nitrogen limit brain size. Evolution 74:2304–2319. DOI: https://dx.doi.org/10.1111/evo.14072
Sol, D., R.P. Duncan, T.M. Blackburn, P. Cassey, and L. Lefebvre. 2005a. Big brains, enhanced cognition, and response of birds to novel environments. Proceedings of the National Academy of Sciences of the United States 102:5460–5465. DOI: https://dxdoi.org/10.1073/pnas.0408145102
Sol, D., L. Lefebvre, and J.D. Rodríguez-Teijeiro. 2005b. Brain size, innovative propensity and migratory behaviour in temperate Palaearctic birds. Proceedings of the Royal Society B: Biological Sciences 272:1433–1441. DOI: https://dx.doi.org/10.1098/rspb.2005.3099
Sol, D., S. Bacher, S.M. Reader, and L. Lefebvre. 2008. Brain size predicts the success of mammal species introduced into novel environments. American Naturalist 172:S63–S71. DOI: https://dx.doi.org/10.1086/588304
Striedter, G.F. 2005. Principles of Brain Evolution. Sinauer Associates Incorporated, USA.
Swanson, E.M., K.E. Holekamp, B.L. Lundrigan, B.M. Arsznov, and S.T. Sakai. 2012. Multiple determinants of whole and regional brain volume among terrestrial carnivorans. PLoS One 7:e38447. DOI: https://dx.doi.org/10.1371/journal.pone.0038447
Timmermans, S., L. Lefebvre, D. Boire, and P. Basu. 2000. Relative size of the hyperstriatum ventrale is the best predictor of feeding innovation rate in birds. Brain, Behavior and Evolution 56:196–203. DOI: https://dx.doi.org/10.1159/000047204
Triki, Z., E. Levorato, W. McNeely, J. Marshall, and R. Bshary. 2019. Population densities predict forebrain size variation in the cleaner fish *Labroides dimidiatus*. Proceedings of the Royal Society B: Biological Sciences 286:20192108. DOI: https://dx.doi.org/10.1098/rspb.2019.2108
Triki, Z., S. Fong, M. Amcoff, and N. Kolm. 2022. Artificial mosaic brain evolution of relative telencephalon size improves inhibitory control abilities in the guppy (*Poecilia reticulata*). Evolution 76:128–138. DOI: https://dx.doi.org/10.1111/evo.14405
Trokovic, N., A. Gonda, G. Herczeg, A. Laurila, and J. Merilä. 2011. Brain plasticity over the metamorphic boundary: Carry-over effect of larval environment on froglet brain development. Journal of Evolutionary Biology 24:1380–1385. DOI: https://dx.doi.org/10.1111/j.1420-9101.2011.02275.x
van den Heuvel, M.P., E.T. Bullmore, and O. Sporns. 2016. Comparative connectomics. Trends in Cognitive Sciences 20:345–361. DOI: https://dx.doi.org/10.1016/j.tics.2016.03.001
Van Woerden, J.T., C.P. Van Schaik, and K. Isler. 2010. Effects of seasonality on brain size evolution: Evidence from strepsirrhine primates. American Naturalist 176:758–767. DOI: https://dx.doi.org/10.1086/657045
Wei, T., V. Simko, M. Levy, Y. Xie, Y. Jin, and J. Zemla. 2017. R package "corrplot": Visualization of a Correlation Matrix. Statistician 56:316–324.
West-Eberhard, M.J. 2003. Developmental Plasticity and Evolution. Oxford University Press, USA.
Wickham, H. 2016. Ggplot2: Elegant Graphics for Data Analysis. Sringer-Verlag, USA.
Wilbur, H.M. 1987. Regulation of structure in complex systems: Experimental temporary pond communities. Ecology 68:1437–1452. DOI: https://dx.doi.org/10.2307/1939227
Won, E.T., and R.J. Borski. 2013. Endocrine regulation of compensatory growth in fish. Frontiers in Endocrinology 4:74. DOI: https://dx.doi.org/10.3389/fendo.2013.00074
Woodley, S.K., B.M. Mattes, E.K. Yates, and R.A. Relyea. 2015. Exposure to sublethal concentrations of a pesticide or predator cues induces changes in brain architecture in larval amphibians. Oecologia 179:655–665. DOI: https://dx.doi.org/10.1007/s00442-015-3386-3

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