



**University of
Zurich**^{UZH}

**Zurich Open Repository and
Archive**

University of Zurich
University Library
Strickhofstrasse 39
CH-8057 Zurich
www.zora.uzh.ch

Year: 2023

Parental provisioning drives brain size in birds

Griesser, Michael ; Drobniak, Szymon M ; Graber, Sereina M ; van Schaik, Carel P

DOI: <https://doi.org/10.1073/pnas.2121467120>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-253187>

Journal Article

Published Version



The following work is licensed under a Creative Commons: Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) License.


Originally published at:

Griesser, Michael; Drobniak, Szymon M; Graber, Sereina M; van Schaik, Carel P (2023). Parental provisioning drives brain size in birds. *Proceedings of the National Academy of Sciences of the United States of America*, 120(2):e2121467120.

DOI: <https://doi.org/10.1073/pnas.2121467120>



Parental provisioning drives brain size in birds

Michael Griesser^{a,b,c,d,1} , Szymon M. Drobniak^{e,f}, Sereina M. Graber^d, and Carel P. van Schaik^{d,g,h}

Edited by Scott Edwards, Harvard University, Cambridge, MA; received December 22, 2021; accepted November 26, 2022

Large brains support numerous cognitive adaptations and therefore may appear to be highly beneficial. Nonetheless, the high energetic costs of brain tissue may have prevented the evolution of large brains in many species. This problem may also have a developmental dimension: juveniles, with their immature and therefore poorly performing brains, would face a major energetic hurdle if they were to pay for the construction of their own brain, especially in larger-brained species. Here, we explore the possible role of parental provisioning for the development and evolution of adult brain size in birds. A comparative analysis of 1,176 bird species shows that various measures of parental provisioning (precocial vs. altricial state at hatching, relative egg mass, time spent provisioning the young) strongly predict relative brain size across species. The parental provisioning hypothesis also provides an explanation for the well-documented but so far unexplained pattern that altricial birds have larger brains than precocial ones. We therefore conclude that the evolution of parental provisioning allowed species to overcome the seemingly insurmountable energetic constraint on growing large brains, which in turn enabled bird species to increase survival and population stability. Because including adult eco- and socio-cognitive predictors only marginally improved the explanatory value of our models, these findings also suggest that the traditionally assessed cognitive abilities largely support successful parental provisioning. Our results therefore indicate that the cognitive adaptations underlying successful parental provisioning also provide the behavioral flexibility facilitating reproductive success and survival.

precocial and altricial birds | cognitive evolution | expensive brain hypothesis | comparative study | brain development

Large brains bring diverse cognitive benefits, including enhanced information acquisition and processing [e.g., stereoscopic vision in primates (1, 2) or electro-sensing in mormyrid fishes (3)], motor control and decision-making (4–7), and cognitive abilities such as learning (8–10) and reasoning (11–13). This effect is supported by comparative studies examining links between brain size and specific eco- or socio-cognitive abilities (14–19). Comparative studies also indicate that these abilities are adaptive by showing a positive association between relative brain size and longevity in diverse lineages (20–22). On a population level, the cognitive benefits of large brains are reflected in the ability to successfully establish populations (23, 24) and have more stable populations (25).

Nonetheless, despite these cognitive benefits, many species have relatively small brains, which may be explained at least in part by the high energetic costs of brain tissue. The expensive brain hypothesis focuses on the link between relative brain size and the energy available to sustaining the adult brain (26). A number of comparative studies support this idea (27–29). These high energy costs of brains may also have developmental consequences. Developing brains do not yet bring the substantial cognitive benefits required to support the high cost of brain growth and maintenance (30, 31). Thus, an immature of a larger-brained species faces a seemingly insurmountable bootstrapping problem: how can it develop a large, functioning brain when it ideally would already have one to provide the energy necessary for this process? Therefore, when applied to development, the expensive brain hypothesis proposes that natural selection cannot always respond to opportunities to evolve specific cognitive adaptations via an increase in brain size, even if this would in principle lead to higher fitness (32).

This catch-22 leads to the hypothesis that adult brain size across species depends on the parents' capacity to provision their young [i.e., via egg size, feeding and keeping the young warm (see ref. 32)]. It makes similar predictions as the maternal energy hypothesis (33), which argues that the ability of mammalian mothers to transfer energy to their offspring constrains brain size. However, this idea did not consider brain size an adaptive trait, only considered some components of parental provisioning, did not compare its predictive power with that of socio- or eco-cognitive selective agents, and did not recognize the bootstrapping problem (32), and thus failed to derive more detailed predictions. Although various subsequent studies have reported links between separate features of maternal allocation and relative brain size in mammals (33, 34), birds (17), cichlid fish

Significance

The young of large-brained species, if left to grow their own brain, would face a seemingly insurmountable energetic constraint, because brain tissue is energetically costly but adequate cognitive benefits arise only after a delay. We therefore hypothesize that protracted parental provisioning was a precondition for the evolution of large brains. Comparative analyses of 1,176 bird species confirmed that parental provisioning strongly predicts variation in relative brain size, suggesting that these two traits coevolved. These results provide an explanation for the well-known but so far unexplained difference in relative brain size between altricial and precocial birds. They also cast doubt on the explanatory value of previously considered social or technological cognitive abilities, suggesting we rethink our approach to cognitive evolution.

Author contributions: M.G. and C.P.v.S. designed research; M.G., S.M.D., S.M.G., and C.P.v.S. performed research; S.M.D. contributed new reagents/analytic tools; M.G., S.M.D., and S.M.G. analyzed data; M.G. and C.P.v.S. acquisition of funding; and M.G., S.M.D., and C.P.v.S. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Copyright © 2023 the Author(s). Published by PNAS. This article is distributed under [Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 \(CC BY-NC-ND\)](https://creativecommons.org/licenses/by-nc-nd/4.0/).

¹To whom correspondence may be addressed. Email: michael.griesser@uni-konstanz.de.

This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2121467120/-/DCSupplemental>.

Published January 6, 2023.

(35), and sharks and rays (36), here we leverage the recently developed parental provisioning hypothesis (32) to provide a comprehensive test that considers all aspects of parental provisioning of young, while at the same time comparing its predictive power for brain size with that of the usually considered eco- and socio-cognitive benefits accruing to adults.

Here, we focus on birds, a lineage that is well suited for an integrated test of these different hypotheses. Birds show appreciable variation in many relevant traits, and the energy transfer from parents to offspring can readily be assessed via egg volumes and the time offspring are provisioned. Moreover, birds have a deeply rooted split in the developmental state of the hatchlings, ranging from precocial (no or little provisioning of the young) to altricial (extended provisioning), henceforth referred to as developmental mode (37). Previous work noted that precocial species have smaller relative brain size than that of altricial ones (38, 39), but the evolutionary causes of this difference remain unclear. Birds also vary in the number of providers (40). These differences allow us to distinguish the effects of investment in eggs from those of provisioning of young. Moreover, birds show major variation in ecology [i.e., aspects of their ecological niche, the climate in their geographic range (41)] and sociality (42).

This high variability in all relevant variables allowed us to simultaneously test their possible effects on adult brain size. We assembled information on adult brain size, adult body mass, predictors assessing parental provisioning (developmental mode, egg mass, clutch size, duration of food provisioning, number of providers), ecology (fiber and energy content of food, complexity of food acquisition, foraging substrate, sedentariness, insularity, climate in the geographic range), and sociality (strength and stability of pair bonds, breeding alone or in colonies, group sizes outside the breeding season) for 1,176 bird species. For the comparative tests, we used phylogenetically controlled Bayesian mixed models (43) to assess the effects on relative brain size across species of i) parental provisioning, ii) eco-social predictors, and iii) all predictors combined. Next, to understand how the different predictors may have influenced each other's evolution, we used phylogenetic d-separation path analysis (44).

Results

Because body mass is tightly correlated with brain size, models using absolute brain size leave little variation left to explain. We therefore report the results using relative brain size scaled by body mass as the response variable, but note that analyses including absolute brain size as a response variable produce qualitatively the same results (*SI Appendix, Table S1 A–C*). Moreover, body mass scales with many aspects of bird physiology and life history in a nonlinear manner. Thus, we include body mass and its interaction with key predictors in all models to capture these nonlinearities.

Phylogenetically controlled mixed models showed that larger relative brain sizes in birds were positively associated with all components of parental provisioning (Fig. 1 and *SI Appendix, Table S2 A–D*). Larger relative brains were found in species that are altricial, have larger relative egg mass and smaller clutches, and feed their young for a longer time. The effect of these predictors was modified by interactions among them, further highlighting the importance of parental provisioning (Fig. 1). Accordingly, only precocial species showed a negative correlation between relative brain size and clutch size (Fig. 2*A*), while only altricial species showed a positive correlation between relative brain size and the time offspring are fed (Fig. 2*B*). The remaining interaction effects reflected fundamental allometries or differences in body mass between precocial and altricial species (Fig. 1). In sum, the total

amount of energy invested into each individual young strongly affected relative adult brain size.

In a separate analysis of the effect of eco-social predictors on relative brain size, phylogenetically controlled mixed models primarily showed that sedentary species and those that forage arboreally had larger relative brain size than those that are migratory or use other foraging substrates (Fig. 2 *C* and *D*). In terms of interaction effects, we found that relative brain size increased with body mass only in arboreal foragers, and that higher energy content of food translated into larger relative brain size only in larger species (Fig. 1). Social factors had a much weaker impact on relative brain size: species with enduring pair bonds tended to have a larger relative brain size than species without pair bonds, whereas no correlations were found for the other social predictors (Fig. 1).

This eco-social model explained markedly less variance in relative brain sizes than the parental provisioning model ($R^2 = 0.38$ vs. $R^2 = 0.50$). However, a combined model containing both parental provisioning and eco-social predictors performed best ($R^2 = 0.57$). Although confirming the patterns of the separate models (Fig. 1), it revealed that the posterior estimates of effect sizes of parental provisioning predictors were far larger than those of the eco-social factors. Among the latter, the ecological predictors that remain significant in the combined model were largely linked to the adult foraging niche and movement patterns, whereas social predictors no longer played any role.

Additional models showed that data limitations are not responsible for the observed patterns. Models that excluded predictors with limited data availability (time fed, social grouping; *SI Appendix, Table S3 A and B*) confirmed the key role of parental provisioning in relative brain size. Similarly, using a more detailed categorization of the developmental mode spectrum instead of binary categorization recovered the same patterns (*SI Appendix, Table S3C*), and so did a model that controlled for the possible confounding effect of longevity on parental provisioning predictors (*SI Appendix, Table S2D*). Finally, lineages may differ in their brain-to-body size allometry (46), which may affect the patterns. However, a model using lineage-specific (47) brain-to-body allometries (*SI Appendix, Table S4*) confirmed the results of the analyses using the overall allometry.

The effect of parental provisioning on relative brain size became obvious when superimposed on a phylogenetic tree (Fig. 3). Starting at 3 o'clock and moving counterclockwise, early emerging, precocial lineages had relatively small brains (Palaeognathae ①, Galloanserae ②, Charadriiformes ④), while interdispersed altricial lineages (Columbimorphes ③, Suliformes, Pelicaniformes, Procellariiformes ④, Strisores ⑥) had slightly larger brains. With the origin of Inopinaves (core land birds: Accipitriformes-Passeriformes ⑨ to ⑭) some 65 Mya (47), systematic altriciality and extensive parental provisioning arose, resulting in several clusters of lineages with notably enlarged relative brain size, including owls, parrots, and corvids, while one lineage (Strisores ⑧) reverted to precociality and small brains. The most recently evolved and highly diverse other passerines were small bodied and did not have brains of exceptionally large relative size, although they are still relatively larger than those of precocial lineages.

Because the predictors analyzed above may not only have affected relative brain size directly, but also have selected for evolutionary changes in values of other predictors and thus affected brain size indirectly, we performed phylogenetic path analyses (44, 48) to gain better insights into the evolutionary relationships between traits. We included well-established developmental and eco-social relationships in all models, but also added biologically plausible ones involving brain size that were varied across the different models.

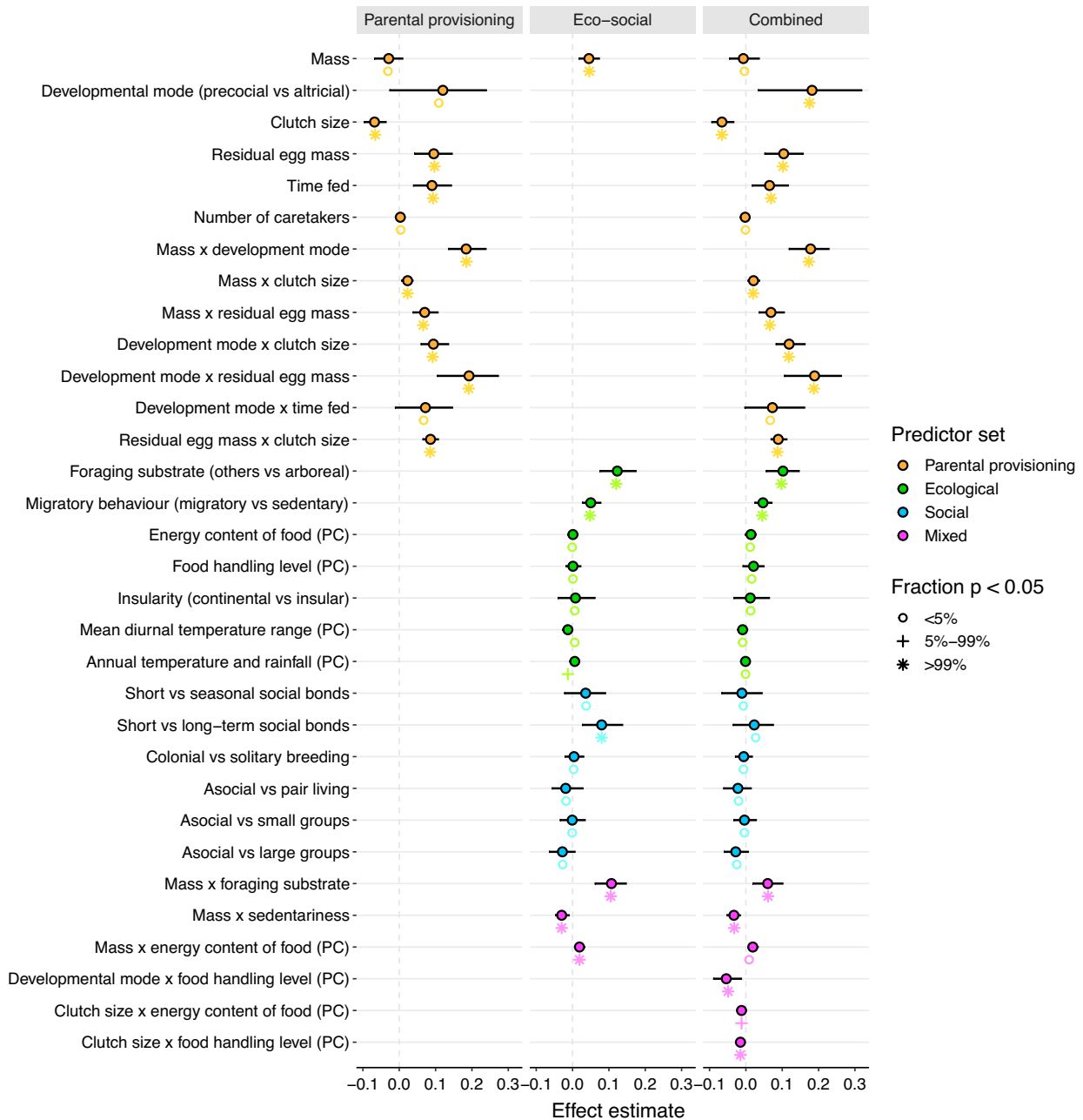


Fig. 1. Estimated coefficients and effect sizes of phylogenetically controlled mixed models of the parental provisioning model, the eco-social model, and the combined model on relative brain size in birds. Color-filled circles denote estimated effects and lines denote the 95% lower and upper confidence limits generated in the R package MCMCglmm (43) based on a consensus phylogeny. Symbols below the circles denote the proportion of random tree models that reach statistical significance ($P < 0.05$) for each predictor based on model averaging of 200 models, using a set of random trees from <http://birdtree.org> (45). The corresponding full models are shown in *SI Appendix, Table S2 A–C*.

The model assessing the relationships among the various parental provisioning predictors of relative brain size showed that adult body mass affects all other traits, including developmental mode (Fig. 4A). Both a large adult body mass and altriciality had a negative effect on clutch size and residual egg mass. Altriciality had a strong positive effect on the time offspring are fed, and subsequently on brain size. These patterns reflect established life history trade-offs and their cascading effects on the total amount of energy transferred from parents to their offspring at the different developmental stages. The remaining effect of body mass on relative brain size depended on developmental mode, reflecting that larger altricial species had larger relative brain sizes than precocial species, relative to what would be predicted from body size alone (Fig. 1).

This pattern therefore fully supports the pervasive effect of parental provisioning on a species' brain size.

Turning to the eco-social predictors, the path model assessing the evolutionary relationships among them showed that some of these predictors have strong evolutionary links among themselves, but rather weak selective effects on relative brain size (Fig. 4B). We note that a model where social predictors and the foraging substrate were a consequence of larger brains did perform significantly less well than the model where these predictors were linked to relative brain size. A combined path analysis (Fig. 5) including both parental provisioning and eco-social predictors retained the relationships revealed by the separate and combined phylogenetically controlled mixed models. Parental provisioning continued

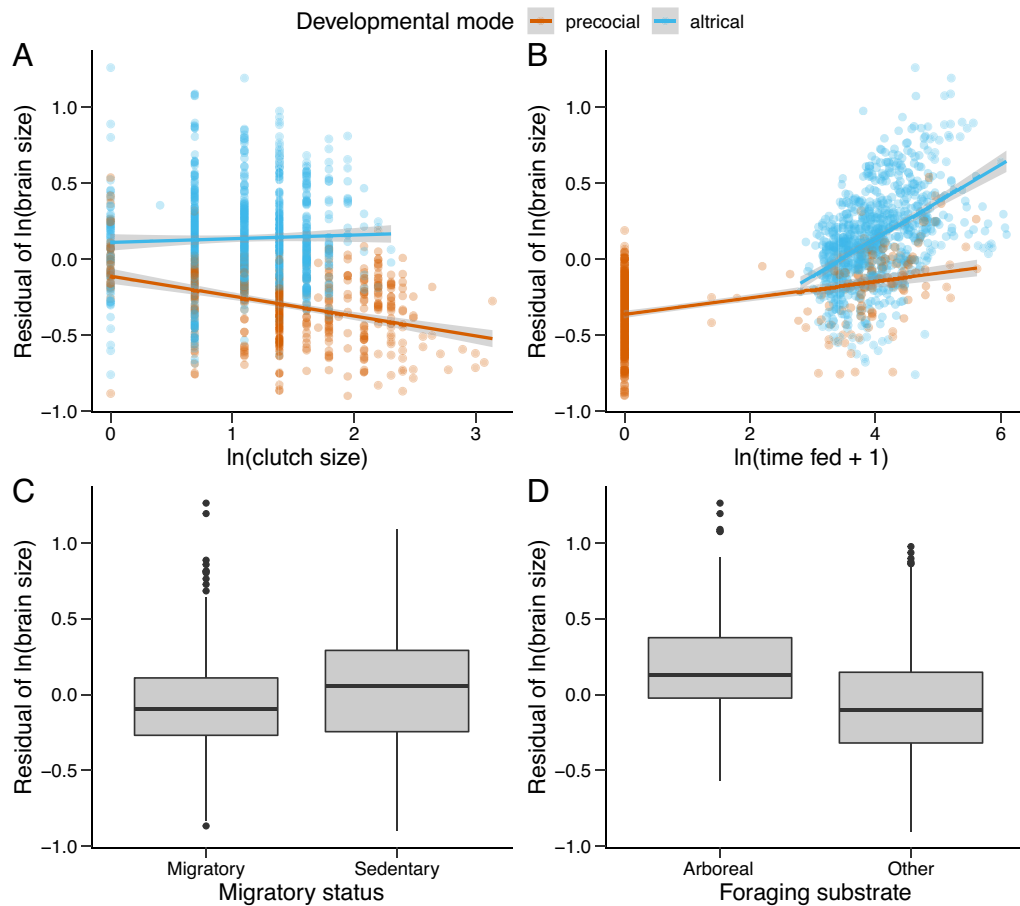


Fig. 2. The effect of parental provisioning (A and B) and ecological predictors (C and D) on relative brain size in birds (N = 1,176 species). A) Clutch size vs. developmental mode [precocial (N = 427 species) vs. altricial (N = 749 species)]. B) Time provisioned vs. developmental mode (precocial vs. altricial). C) Movement pattern: sedentary (N = 566 species) vs. migratory (N = 610 species). D) Foraging substrate: others (N = 929 species; including terrestrial, aerial, aquatic foraging) vs. arboreal (N = 247 species). In A and B, solid lines designate linear trend estimates, gray shading designates SE bands. In C and D, thick lines designate medians, the gray boxes designate interquartile ranges (Interquartile Range IQR, 0.25 to 0.75 quantile), whiskers designate ± 1.5 IQR, circles designate outliers.

to have a direct and strong effect on relative brain size, whereas that of the eco-social variables remained weak.

Discussion

For animals, developing and maintaining brains, particularly large ones, is energetically demanding (30, 31) during a time when they are still developing the requisite cognitive abilities to acquire the energy. This creates a bootstrapping problem. The parental provisioning hypothesis (32) highlights the pivotal role of the energy invested by parents into the development of their young in overcoming this bootstrapping problem. Large brains can therefore only evolve in species where parents are capable of sustaining both themselves and their growing young, and this process is supported by the cognitive abilities large brains produce. Consequently, the proximate and ultimate drivers of brain size are tightly linked and no clear distinction between them is possible (32).

The analyses reported here confirm the predictions of the parental provisioning hypothesis, and the results have three major implications, which we now discuss in turn. First, parental provisioning is the main predictor of adult relative brain size in birds: in the combined model, adult eco- and socio-cognitive demands hardly play a role. Thus, large brains can only be sustained in species with extensive energy inputs during development. This association is supported by previous work in mammals (34), birds (17), fish (35), as well as sharks and rays (36). However, these studies

overlooked the bootstrapping problem faced by the developing young (33, 34). The parental provisioning hypothesis offers a theoretical underpinning to this pattern (32). Parental provisioning enables the growing young to construct a large brain during a life stage when they themselves have not yet learned the skills needed to acquire the energy necessary to sustain such a growing and learning brain. Accordingly, parental provisioning removed this bottleneck for the evolution of larger brain size and enabled bird species to evolve into skill-intensive niches, as evident by the diverse foraging and nesting habits of altricial species compared to precocial species (49). The importance of parental provisioning is also highlighted by the phylogenetic path analyses, which confirm that its components form a tightly coevolved set.

Second, the parental provisioning hypothesis provides an explanation for the well-established but so far unexplained pattern that altricial species have relatively larger brains than precocial species (38, 39), and that altricial species have steeper brain–body allometric slopes (32, 50). Altricial young are provisioned by their parents until they have reached adult size. In contrast, most precocial young are only provisioned through egg mass, which is subject to obvious physical limitations. As a result, precocial species experience serious constraints on the evolution of relative brain size and therefore niche complexity (49). The evolutionary transitions to altriciality allowed species to evolve into cognitively more demanding niches, which require more elaborate food-handling or antipredator skills (39). This was made possible by parents

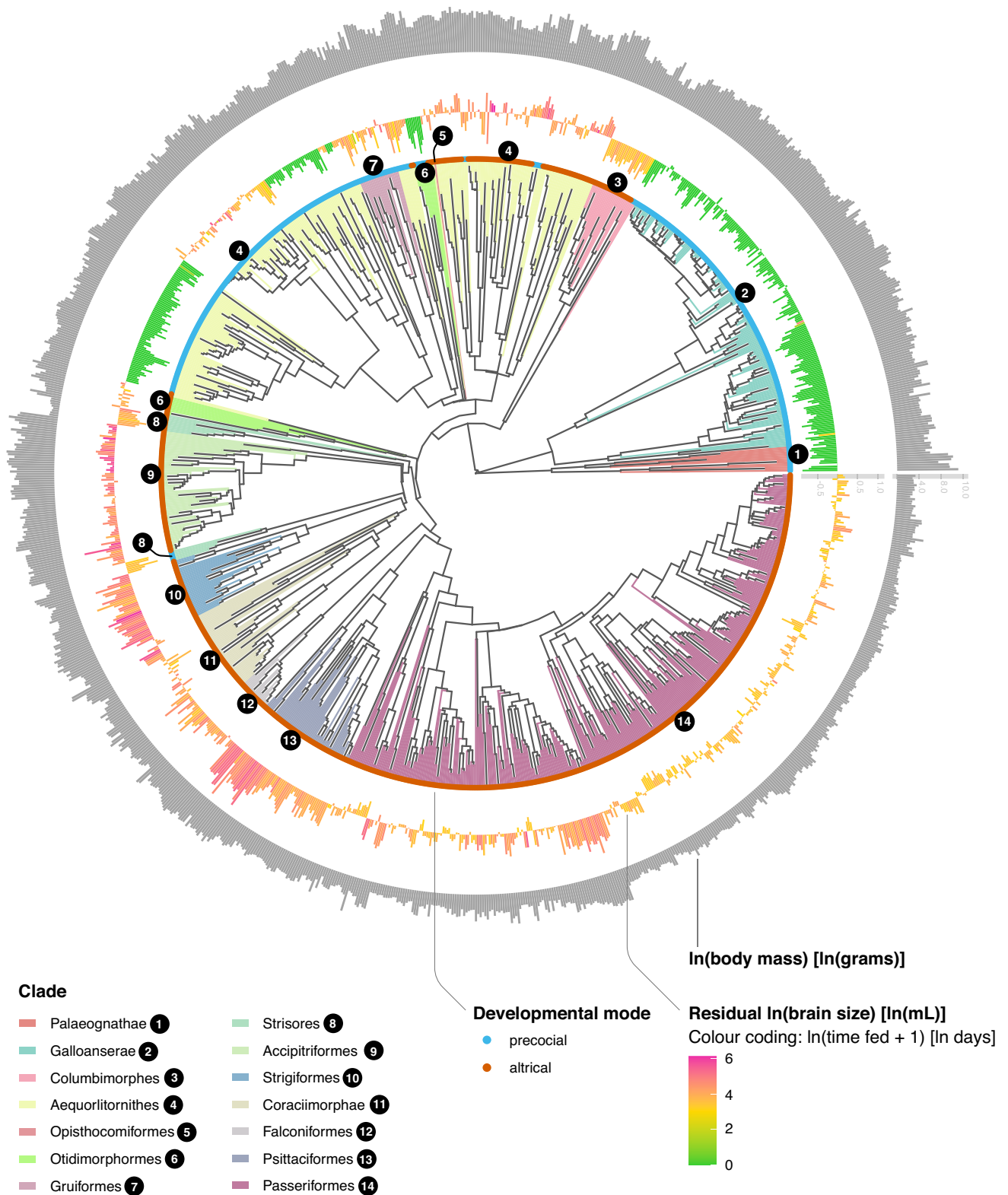


Fig. 3. Phylogenetic distribution of relative brain size, developmental mode (precocial vs. altricial), and time parent(s) feed their offspring (N = 1,176 bird species). Size of bars in outer circle represents body mass [$\ln(\text{grams})$]; size of bars in middle circle represents relative brain size [$\ln(\text{mL})$], while their color represents the time parents feed their offspring [$\ln(\text{days} + 1)$]; inner circle represents developmental mode (precocial, altricial). Phylogeny follows <http://birdtree.org> (45), whereas taxonomy largely follows Prum et al. (47), explaining why some clades appear polyphyletic.

donating the requisite large brain to their offspring through extended parental provisioning. However, these transitions were actually quite rare (39). Although the underlying reasons for this rarity remain unclear, we speculate that precocial species remain stuck in a simple ecological niche (49) unless they find a way to

breed in safer places, which facilitates the evolution of provisioning and therefore altriciality.

Finally, our findings imply a modest role at best for socio- and eco-cognitive abilities in the evolution of brain size in birds. We found almost no detectable effect of the cognitive demands of

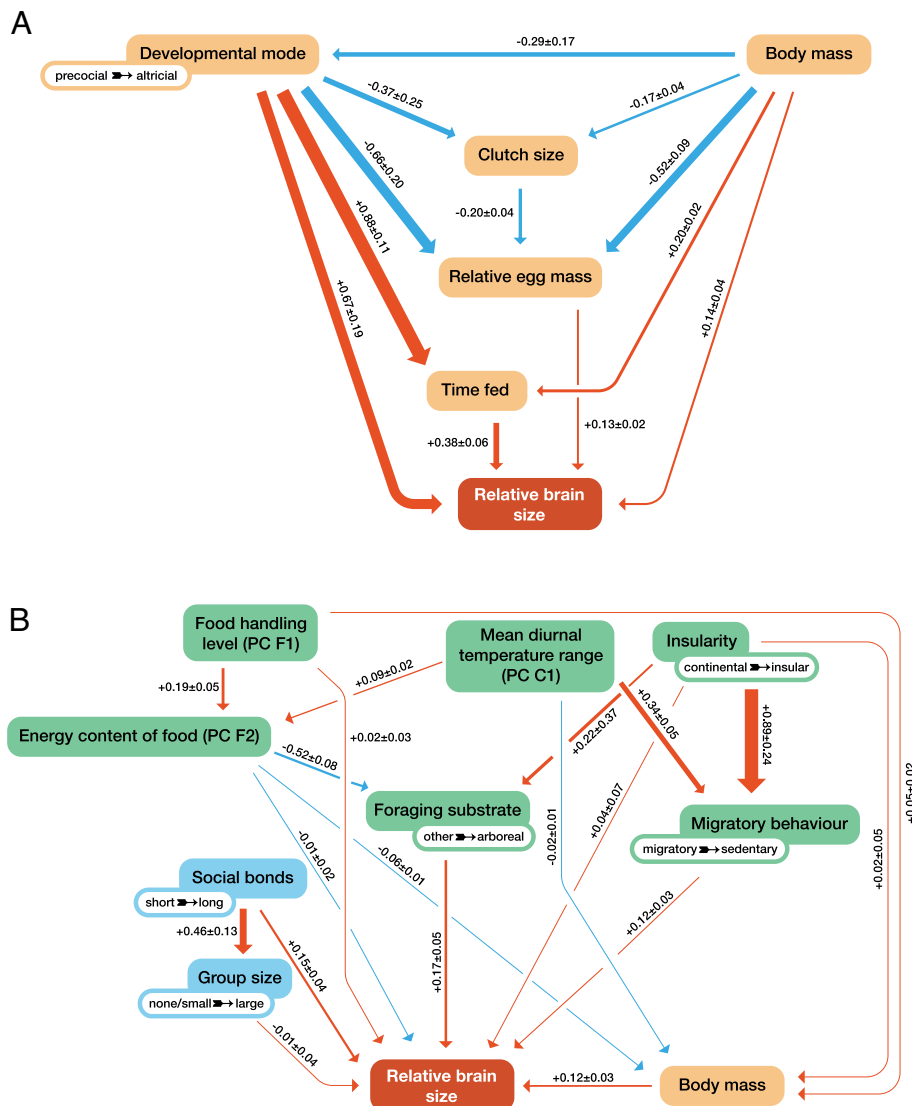


Fig. 4. Phylogenetic associations among specific predictor sets and relative brain size, assessed by d-separation path analyses (44) ($N = 1,176$ bird species). Arrow thickness and numeric values show the strength of the association, arrow color shows its direction (positive: orange, negative: blue). *A*, Associations among parental provisioning predictors. *B*, Associations among eco-social predictors.

adult social life. We did, however, find weak evidence for effects of eco-cognitive predictors independent of parental provisioning that affect the energy balance of adults. First, migratory species have smaller brains than resident species (51), indicating that the high energy cost of migration reduces the ability to sustain a large adult brain. Second, the effect of arboreal foraging may be more related to adult survival, as in mammals (52), thus removing a constraint on brain enlargement.

The absence of an effect of the traditionally measured socio- and eco-cognitive variables on relative brain size is puzzling. It may actually reflect a more general problem in comparative cognition, as popular tests often fail to produce a differentiation between species generally thought to show major differences (53). Thus, these tests may not assess those cognitive adaptations that produce fitness benefits by scaffolding critical foraging and predation-avoidance skills and improving the ability to provision the young and/or improve survival. Our results suggest we should pay closer attention to cognitive adaptations such as general behavioral flexibility [as enabled by executive functions and domain-general intelligence (13)], including the coordination of parental duties (essentially linked to planning, decision-making,

and time management). These cognitive abilities may be expressed behaviorally in avoidance of predation on eggs, nestlings, and adults (54, 55); in maximization of food intake under ever-changing food and weather conditions; or in the socio-cognitive ability to coordinate offspring provisioning (14). For example, birds can flexibly adjust parenting in response to predation risk to themselves and their nestlings (56), as confirmed experimentally (57). However, because these cognitive abilities are not readily estimated in a way that can be compared across many species, they are so far not included in comparative analyses of brain size evolution.

To conclude, the amount and duration of parental provisioning is the key to understand brain size evolution in birds, and likely also more generally (32). Across animal lineages, the evolution of parental provisioning beyond eggs (i.e., altricial birds, mammals, cartilaginous fishes) coevolved with major shifts in brain size (32). Moreover, the increase in the number of caregivers during human evolution and the provisioning of children well into adolescence (58) may have largely enabled the massive increase in relative brain size in our lineage over the last 2.5 My (59).

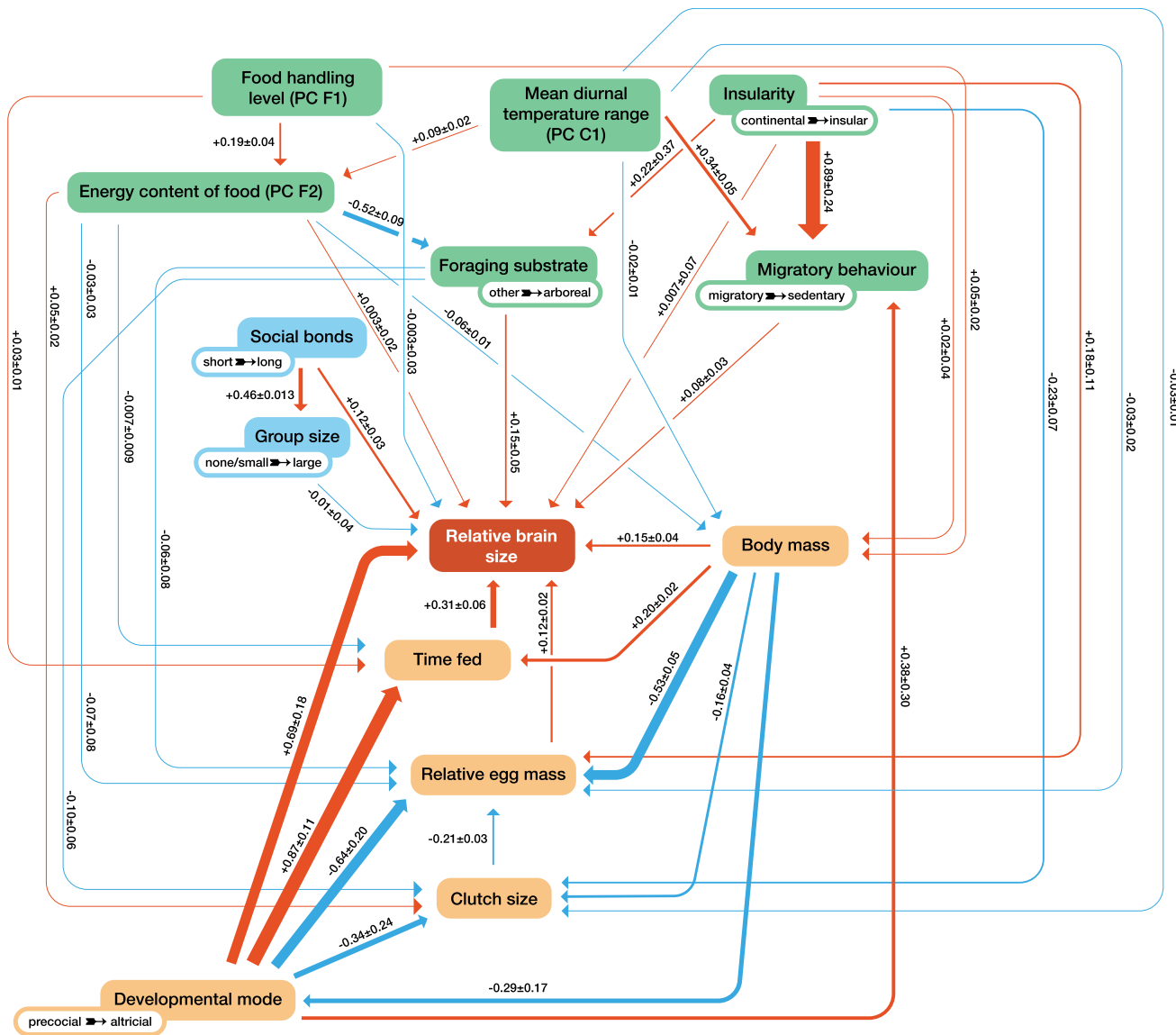


Fig. 5. Phylogenetic associations among parental provisioning (orange), ecological and social predictors (green), and relative brain size, assessed by d-separation path analyses (44) (N = 1,176 bird species). Arrow thickness and numeric values show the strength of the association, arrow color its direction (orange: positive, blue: negative).

Materials and Methods

Data Collection. We gathered information quantifying parental provisioning and the socio-ecological correlates identified by previous work as influencing brain size in animals. We collected these data from the online version of the Handbooks of the Birds of the World (60), region-specific handbooks (61, 62), existing published datasets (42, 63–65), as well as species-specific studies listed in the dataset. Data on brain size were collected from three sources (19, 66, 67).

The following parental provisioning predictors were included: adult body mass, developmental mode, egg mass, clutch size, the time offspring are fed by their parents until nutritional independence, and the number of caretakers. We did not use imputed data based on mean values of related species, which limited our sample size compared to other comparative studies. Adult body mass data were calculated as means if mass of males and females was listed separately. The developmental mode was assessed dichotomously. Precocial species are those which hatch with open eyes and abandon the nest within 2 d after hatching, and here also encompass semi-precocial species (the young hatch with open eyes and are soon capable of walking, but they remain in the nest to be fed by parents). Altricial species are those in which the young hatch with closed eyes and largely lack feathers and are fed by parents in the nest, and here also encompass semi-altricial species (the young hatch with open eyes and are feathered, but

remain in the nest to be fed by their parents) (39). Given that this dichotomous split could obscure patterns, we did rerun the main analyses using all the four categories (fully precocial, semi-precocial, semi-altricial, and fully altricial; see *SI Appendix, Table S3C*). Egg mass was either assessed through direct measurements of egg mass or was calculated based on egg dimension measurements, using the formula by Hoyt (68). For those species where multiple egg dimension measurements were available in the literature, the mean values of all provided measurements were used. For those species where egg dimension or mass data were not available in handbooks, we used information in published data compilations listed in the dataset (65, 69–71). Clutch size data corresponded to the median clutch size (55, 71). The time young are fed by their parents included both the time parents provision their young in the nest and thereafter until the young are nutritionally independent from their parents, as reported in handbooks (see above), and published datasets (38). We also included the mean number of caretakers, where mound-nesting species had zero caretakers, species with uniparental care one, species with bi-parental care two, and cooperatively breeding species the mean value of caretakers. These data were obtained from handbooks (60), existing datasets (40, 67), and species-specific studies listed in the dataset.

Based on previous studies on the drivers of brain size in vertebrates, the following ecological predictors were included: food energy, fiber content of food, number of processing steps required to extract food, foraging substrate,

sedentariness, insularity, and climatic predictors. The predictors relating to food were calculated based on a published database (63). We calculated the mean energy and fiber content of foods per 100 g from previous studies (72, 73), as well as the number of processing steps required to extract food (74). Given that these three predictors are highly correlated (i.e., low caloric food usually has a high fiber content and requires only a single processing step; *SI Appendix, Fig. S1*), we used a Principal Component Analyses (PCA) approach and extracted two independent Principal Components (PCs) from these predictors (see below). The foraging substrate data were obtained from a published database (64). We categorized species into those that forage arboreally, compared to all other foraging substrates. In mammals, arboreal foraging has been shown to be associated with increased longevity, which in turn allows the evolution of larger brains (52). Sedentariness was assessed based on the maximum movement pattern of a species, separating sedentary species (including local movements) from migratory species (short- and long-distance migrants, altitudinal migrants), combining data from three sources (42, 64, 66). In addition, we also included data on the insularity of species, distinguishing continental from insular species (18, 64). Missing data were directly obtained from the primary sources listed above. Finally, we included data on the climate in the species' geographic range (75, 76), using a PCA approach (see below). Values of species with contradicting values in different published datasets were confirmed based on the literature listed above, using the above definitions.

The social predictors were also based on previous studies and included social bond strength, group size, and solitary vs. colonial breeding. Social bond data were based on published data (77), separating species with short bonds during mating only, seasonal bonds, and long-term bonds that extend beyond a single breeding season. The grouping patterns of species outside the breeding season distinguished between asocial species (usually on their own), pair living species (usually in pairs), species that live in small groups (usually 3 to 30 individuals), and large groups (usually more than 30 individuals). The split between small and large groups should capture the difference between personalized groups where group members know each other individually, including family groups (42) and ephemeral and/or anonymous groups. We also included whether species breed singly or whether they breed in colonies.

Analyses. All statistical analyses were carried out in the R 4.0.2 environment (78). The analyses were structured as a series of linear models with increasing complexity, all including phylogenetic relatedness across species [in the form of a phylogenetic correlation matrix based on well-resolved avian phylogenetic trees (45)]. For predictors that are expected to be allometrically linked to body mass (brain size, egg mass), the models included their residuals from regressions against body mass. Brain size (the response variable) and adult body mass were log transformed prior to extracting relative brain sizes. All continuous predictors were mean centered and scaled to a SD of one, to aid in the interpretation of intercepts and the comparison of effect sizes. The three predictors relating to food (food energy, fiber content, and food-handling levels) were strongly collinear (*SI Appendix, Fig. S1 A-D and Table S5A*). Thus, we used a principal component analysis in the package psych (79) (using varimax rotation) to reduce these predictors to two uncorrelated components. Based on their loadings, the resulting two components describe the energy content of food and the food-handling levels (including the absence of fibers) (*SI Appendix, Table S5A*). Using the same approach, we extracted three uncorrelated components from 14 climatic predictors. PC1 reflects a latitudinal gradient from the tropics to high latitudes. PC2 reflects interannual variability. PC3 reflects a gradient from dry, open, and highly seasonal environments to stable and closed environments (*SI Appendix, Table S5B*).

We fitted three phylogenetically controlled mixed models that assessed the dependence of relative brain size on provisioning predictors (model 1), eco-social predictors (model 2), and a combination of both (model 3). Each model included a set of main effects and first-order interactions with meaningful biological interpretation (see *SI Appendix, Tables S1-S4* for a full list of predictors and interactions in each of the models). Since the size of models (both in terms of data and numbers of predictors) prevented a full search of all predictor combinations via selection based on information criteria (IC), we conducted backward simplification of models, removing nonsignificant interactions (starting with the ones having the largest prediction error). To remain conservative, we did not remove nonsignificant main effects. Backward selection has been shown to perform well in comparison to IC-based model selection in similar contexts (80) and is robust in cases where the number of individual observations exceeds several fold the number of estimated

predictors, as is the case here. We report final outputs of the most parsimonious models (Fig. 1 and *SI Appendix, Tables S1-S4*). All models were fitted using an Markov chain Monte Carlo (MCMC) based mixed modeling approach using the package MCMCglmm (43). We used chains of 50,000 iterations, with the first 10,000 iterations discarded as burn-ins and thinned every 40 iterations. Visual inspection of the final MCMC samples did not show any sign of autocorrelation. All effective sample sizes were close to the actual numbers of sampled draws from predictors' posteriors (*SI Appendix, Tables S1-S4*). In all models, inverse-gamma priors were used for residual variances (parametrized as inverse-Wishart with $V = 1$ and $\nu = 0.002$). The prior for phylogenetic effect was formed as a weakly informative half-Cauchy density (parameter expanded priors with $V = 1$, $\nu = 1$, $\alpha_{\mu} = 0$, and $\alpha_{\nu} = 10,000$). Priors for fixed effects were left as default (Gaussian densities with $\mu = 0$ and large variance). Using a modification of the variance inflation factor (VIF) analysis adjusted to the phylogenetic comparative mixed model used, we verified that none of the other predictors were significantly collinear, as all Variance Inflation factor (VIF) values were < 2 (*SI Appendix, Table S6*).

The necessity of complete information on all predictors reduced the sample size of the main models to 1,176 species. Thus, we fitted additional models excluding those predictors that most strongly limited our sample size: excluding duration of parental provisioning ($N = 1,458$ species; *SI Appendix, Table S3A*) and excluding duration of parental provisioning and social grouping ($N = 1,594$ species; *SI Appendix, Table S3B*). Both models recaptured the patterns observed in the full model (*SI Appendix, Table S2*), confirming that our sample was not biased by limited data.

The brain-to-body size allometries have been shown to differ across lineages, partly reflecting differences in overall body size across them (46) and partly reflecting the lower parental provisioning in precocial ones (39). These differences may affect our analyses as the residual brain size of larger species in lineages with overall more shallow brain-to-body size slopes will be increasingly overestimated when using an overall Aves-wide allometry to estimate it. Thus, we did rerun the key models using lineage-specific brain-to-body allometries to estimate their residual brain sizes. We used the following monophyletic lineages: Accipitriformes, Aequorlitorinithes, Columbimorphes, Coraciimorphae, Falconiformes, Galloanserae, Gruiformes, Opisthocomiformes, Otidimorphes, Palaeognathae, Passeriformes, Psittaciformes, Strigiformes, Strisores (see ref. 46).

Subsequent to the phylogenetically controlled mixed models, we conducted phylogenetic path analyses to assess the evolutionary links among the predictors included in parental provisioning, the eco-social and the combined model. For each model, we defined a set of d-separation statements (44, 48, 81), describing a hypothesis represented by a directed acyclic graph, linking all involved predictors with an assumed causal link. Given the large number of predictors used in the phylogenetic mixed models, we built the different models using three criteria: i) we grouped the variables into social, eco-climatic, and life history traits; ii) we fixed certain relationships between variables based on established patterns (e.g., the island rule linking body size with island/mainland lifestyle, body mass link with the developmental mode); and iii) we explicitly varied only those paths that directly reflected our hypotheses. Thus, the sequence of models considered reflects hypotheses related to brain size predictors, as outlined in *SI Appendix, Figs. S2-S4*. We considered mostly models where brain size is a consequence of eco-social predictors, but our set included also models where social predictors and the foraging substrate/food energy content were a consequence of brain size.

The models were implemented as sets of phylogenetic linear mixed models fitted in the ASReml-R package (82). In models involving binary responses (e.g., precocial/altricial), we used generalized linear mixed models with probit link function to fit models, which makes their regression coefficients directly comparable with standardized regression coefficients from general linear models for continuous predictors. Since all continuous predictors were scaled to unit SD, results for categorical predictors can be interpreted as standardized Cohen's d effect sizes and, thus, can be directly compared with continuous standardized regression coefficients. The best-fitting hypothesis in each model set was determined via comparisons of their $CICc$ [corrected Fisher's C Information Criterion, a path analysis analog of the Akaike Information Criterion (48)]. In the parental provisioning and eco-social model, the best model was clearly supported over the alternatives ($\Delta CICc > 2$ for top models). In the combined model, two models were clearly supported over the alternatives, but were conceptually identical (*SI Appendix, Table S7*).

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

ACKNOWLEDGMENTS. We thank all field biologists who collected all the natural history data underlying this study. We thank Uri Roll for sharing climatic data, and three anonymous reviewers as well as Jeroen Smaers and F. Stephen Dobson for insightful comments on earlier drafts. This work was supported by a Heisenberg grant no. GR 4650/2-1 by the German Research Foundation DFG to M.G., the Polish National Science Centre, grant no. UMO-2015/18/E/NZ8/00505 to S.M.D., the Australian Research Council DECRA award no. DE180100202 to S.M.D., the University of Zurich to C.P.v.S., and a Max Planck Fellowship to C.P.v.S.

1. R. A. Barton, Binocularity and brain evolution in primates. *Proc. Natl. Acad. Sci. U.S.A.* **101**, 10113–10115 (2004).
2. E. C. Kirk, Visual influences on primate encephalization. *J. Hum. Evol.* **51**, 76–90 (2006).
3. K. V. Sukhum, J. Shen, B. A. Carlson, Extreme enlargement of the cerebellum in a clade of teleost fishes that evolved a novel active sensory system. *Curr. Biol.* **28**, 3857–3863.e3853 (2018).
4. S. T. Parker, Re-evaluating the extractive foraging hypothesis. *New Ideas Psychol.* **37**, 1–12 (2015).
5. S. E. Overington, J. Morand-Ferron, N. J. Boogert, L. Lefebvre, Technical innovations drive the relationship between innovativeness and residual brain size in birds. *Animal Behav.* **78**, 1001–1010 (2009).
6. S. M. Reader, K. N. Laland, Social intelligence, innovation, and enhanced brain size in primates. *Proc. Natl. Acad. Sci. U.S.A.* **99**, 4436–4441 (2002).
7. S. A. Heldstab *et al.*, Manipulation complexity in primates coevolved with brain size and terrestriality. *Sci. Rep.* **6**, 1–9 (2016).
8. B. Rensch, Increase of learning capability with increase of brain-size. *Am. Nat.* **90**, 81–95 (1956).
9. W. I. Riddell, K. G. Corl, Comparative investigation of the relationship between cerebral indices and learning abilities. *Brain Behav. Evol.* **14**, 385–398 (1977).
10. S. Benson-Amram, B. Dantzer, G. Stricker, E. M. Swanson, K. E. Holekamp, Brain size predicts problem-solving ability in mammalian carnivores. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2532–2537 (2016).
11. R. O. Deaner, K. Isler, J. Burkart, C. Van Schaik, Overall brain size, and not encephalization quotient, best predicts cognitive ability across non-human primates. *Brain Behav. Evol.* **70**, 115–124 (2007).
12. S. M. Reader, Y. Hager, K. N. Laland, The evolution of primate general and cultural intelligence. *Philos. Trans. R. Soc. B Biol. Sci.* **366**, 1017–1027 (2011).
13. J. M. Burkart, M. N. Schubiger, C. P. van Schaik, The evolution of general intelligence. *Behav. Brain Sci.* **40** (2017).
14. R. I. Dunbar, S. Shultz, Evolution in the social brain. *Science* **317**, 1344–1347 (2007).
15. S. Shultz, R. Dunbar, Encephalization is not a universal macroevolutionary phenomenon in mammals but is associated with sociality. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 21582–21586 (2010).
16. R. I. Dunbar, The social brain hypothesis. *Evol. Anthropol. Issues, News Rev.* **6**, 178–190 (1998).
17. S. Shultz, R. I. Dunbar, Social bonds in birds are associated with brain size and contingent on the correlated evolution of life-history and increased parental investment. *Biol. J. Linn. Soc.* **100**, 111–123 (2010).
18. F. Sayol, P. A. Downing, A. N. Iwaniuk, J. Maspons, D. Sol, Predictable evolution towards larger brains in birds colonizing oceanic islands. *Nat. Commun.* **9**, 2820 (2018).
19. T. S. Fristoe, C. A. Botero, Alternative ecological strategies lead to avian brain size bimodality in variable habitats. *Nat. Commun.* **10**, 1–9 (2019).
20. P. Minias, P. Podlaszczuk, Longevity is associated with relative brain size in birds. *Ecol. Evol.* **7**, 3558–3566 (2017).
21. X. Yu *et al.*, Large-brained frogs mature later and live longer. *Evolution* **72**, 1174–1183 (2018).
22. N. L. Barrickman, M. L. Bastian, K. Isler, C. P. van Schaik, Life history costs and benefits of encephalization: A comparative test using data from long-term studies of primates in the wild. *J. Hum. Evol.* **54**, 568–590 (2008).
23. D. Sol, R. P. Duncan, T. M. Blackburn, P. Cassey, L. Lefebvre, Big brains, enhanced cognition, and response of birds to novel environments. *Proc. Natl. Acad. Sci. U.S.A.* **102**, 5460–5465 (2005).
24. D. Sol, S. Bacher, S. M. Reader, L. Lefebvre, Brain size predicts the success of mammal species introduced into novel environments. *Am. Nat.* **172**, S63–S71 (2008).
25. T. S. Fristoe, A. N. Iwaniuk, C. A. Botero, Big brains stabilize populations and facilitate colonization of variable habitats in birds. *Nat. Ecol. Evol.* **1**, 1706–1715 (2017).
26. K. Isler, C. P. van Schaik, The expensive brain: A framework for explaining evolutionary changes in brain size. *J. Hum. Evol.* **57**, 392–400 (2009).
27. J. T. van Woerden, E. P. Willems, C. P. van Schaik, K. Isler, Large brains buffer energetic effects of seasonal habitats in catarrhine primates. *Evol. Int. J. Org.* **66**, 191–199 (2012).
28. S. A. Heldstab, K. Isler, C. P. van Schaik, Hibernation constrains brain size evolution in mammals. *J. Evol. Biol.* **31**, 1582–1588 (2018).
29. S. A. Heldstab, K. Isler, S. M. Graber, C. Schuppli, C. P. van Schaik, The economics of brain size evolution in vertebrates. *Curr. Biol.*, in press.
30. A. L. Bauernfeind *et al.*, Aerobic glycolysis in the primate brain: Reconsidering the implications for growth and maintenance. *Brain. Struct. Funct.* **219**, 1149–1167 (2014).
31. J. W. Mink, R. J. Blumenschine, D. B. Adams, Ratio of central nervous system to body metabolism in vertebrates: Its constancy and functional basis. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **241**, R203–R212 (1981).
32. C. P. van Schaik *et al.*, Parental provisioning helps to explain evolutionary variation in brain size. *EcoEvoRxiv [Preprints]* (2022). <https://doi.org/10.32942/osf.io/642xb> Accessed 14 August 2022.
33. R. D. Martin, Scaling of the mammalian brain: The maternal energy hypothesis. *Physiology* **11**, 149–156 (1996).
34. R. A. Barton, I. Capellini, Maternal investment, life histories, and the costs of brain growth in mammals. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 6169–6174 (2011).
35. M. Tsuboi *et al.*, Comparative support for the expensive tissue hypothesis: Big brains are correlated with smaller gut and greater parental investment in Lake Tanganyika cichlids. *Evolution* **69**, 190–200 (2015).
36. C. G. Mull, K. E. Yopak, N. K. Dulvy, Maternal investment, ecological lifestyle, and brain evolution in sharks and rays. *Am. Nat.* **195**, 1056–1069 (2020).
37. A. Portmann, Etudes sur la cérébralisation chez les oiseaux. III Cérébralisation et mode ontogénétique. *Auda* **15**, 1–171 (1947).
38. A. N. Iwaniuk, J. E. Nelson, Developmental differences are correlated with relative brain size in birds: A comparative analysis. *Can. J. Zool.* **81**, 1913–1928 (2003).
39. J. M. Starck, R. E. Ricklefs, *Avian Growth and Development: Evolution within the Altricial-Precocial Spectrum* (Oxford University Press, 1998).
40. A. Cockburn, Prevalence of different modes of parental care in birds. *Proc. R. Soc. B Biol. Sci.* **273**, 1375–1383 (2006).
41. A. L. Pigot *et al.*, Macroevolutionary convergence connects morphological form to ecological function in birds. *Nat. Ecol. Evol.* **4**, 230–239 (2020).
42. M. Griesser, S. M. Drobnik, S. Nakagawa, C. A. Botero, Family living sets the stage for cooperative breeding and ecological resilience in birds. *PLoS Biol.* **15**, e2000483 (2017).
43. J. D. Hadfield, MCMC methods for multi-response generalized linear mixed models: The MCMCglmm R package. *J. Stat. Software* **33**, 1–22 (2010).
44. A. V. Hardenberg, A. Gonzalez-Voyer, Disentangling evolutionary cause-effect relationships with phylogenetic confirmatory path analysis. *Evol. Int. J. Org.* **67**, 378–387 (2013).
45. W. Jetz, G. H. Thomas, J. B. Joy, K. Hartmann, A. O. Moores, The global diversity of birds in space and time. *Nature* **491**, 444–448 (2012).
46. D. T. Ksepka, Tempo and pattern of avian brain size evolution. *Curr. Biol.* **30**, 2026–2036.e2023 (2020).
47. R. O. Prum *et al.*, A comprehensive phylogeny of birds (Aves) using targeted next-generation DNA sequencing. *Nature* **526**, 569 (2015).
48. B. Shipley, The AIC model selection method applied to path analytic models compared using ad-separation test. *Ecology* **94**, 560–564 (2013).
49. J. Starck, "Evolution of avian ontogenies" in *Current Ornithology* (Springer, 1993), pp. 275–366.
50. P. M. Nealen, R. E. Ricklefs, Early diversification of the avian brain: Body relationship. *J. Zool.* **253**, 391–404 (2001).
51. O. Vincze, Light enough to travel or wise enough to stay? Brain size evolution and migratory behavior in birds. *Evolution* **70**, 2123–2133 (2016).
52. C. P. van Schaik, R. O. Deaner, "Life history and brain evolution" in *Animal Social Complexity: Intelligence, Culture, and Individualized Societies*, F. B. M. de Waal, P. L. Tyack, Eds. (2003), pp. 1–25.
53. C. Fichtel, K. Dinter, P. M. Kappeler, The lemur baseline: How lemurs compare to monkeys and apes in the Primate Cognition Test Battery. *PeerJ* **8**, e10025 (2020).
54. T. E. Martin, J. V. Briskie, Predation on dependent offspring. *Ann. N.Y. Acad. Sci.* **1168**, 201–217 (2009).
55. M. Valcu, J. Dale, M. Griesser, S. Nakagawa, B. Kempenaers, Global gradients of avian longevity support the classic evolutionary theory of ageing. *Ecography* **37**, 930–938 (2014).
56. S. L. Lima, Predators and the breeding bird: Behavioral and reproductive flexibility under the risk of predation. *Biol. Rev.* **84**, 485–513 (2009).
57. S. Eggers, M. Griesser, J. Ekman, Predator-induced plasticity in nest visitation rates in the Siberian jay (*Perisoreus infaustus*). *Behav. Ecol.* **16**, 309–315 (2005).
58. H. Kaplan, K. Hill, J. Lancaster, A. M. Hurtado, A theory of human life history evolution: Diet, intelligence, and longevity. *Evol. Anthropol. Issues News Rev.* **9**, 156–185 (2000).
59. K. Isler, C. P. Van Schaik, How our ancestors broke through the gray ceiling: Comparative evidence for cooperative breeding in early homo. *Curr. Anthropol.* **53**, S453–S465 (2012).
60. J. Del Hoyo, A. Elliot, J. Sargatal, D. A. Christie, *Handbook of the Birds of the World* (Lynx Edicions, Barcelona, 2011).
61. P. A. R. Hockey, W. J. J. Dean, P. G. Ryan, *Roberts Birds of Southern Africa* (Trustees of the John Voelcker Bird Book Fund, Cape Town, 7th ed., 2005).
62. P. J. Higgins, S. Marchant, J. M. Peter, S. Cowling, J. Davies, *Handbook of Australian, New Zealand & Antarctic Birds* (Oxford University Press, 2007).
63. H. Wilman *et al.*, EltonTraits 1.0: Species-level foraging attributes of the world's birds and mammals. *Ecology* **95**, 2027–2027 (2014).
64. J. A. Tobias, A. L. Pigot, Integrating behaviour and ecology into global biodiversity conservation strategies. *Philos. Trans. R. Soc. B Biol. Sci.* **374**, 20190012 (2019).
65. T. Lislevand, J. Figuerola, T. Székely, Avian body sizes in relation to fecundity, mating system, display behavior, and resource sharing. *Ecology* **88**, 1605–1605 (2007).
66. F. Sayol *et al.*, Environmental variation and the evolution of large brains in birds. *Nat. Commun.* **7**, 13971 (2016).
67. S. Graber, "Social and ecological aspects of brain size evolution: A comparative approach" in *Department of Anthropology* (University of Zurich, Zurich, 2017), p. 182.
68. D. F. Hoyt, Practical methods of estimating volume and fresh weight of bird eggs. *The Auk* **96**, 73–77 (1979).
69. K. Schläpfer, *The Colorful Eggs of the Tinamou* (Published by author, Engelburg, Switzerland, 2017).
70. J.-Y. Juang *et al.*, The avian egg exhibits general allometric invariances in mechanical design. *Sci. Rep.* **7**, 1–11 (2017).
71. C. Brown, P. Bridgeford, S. Braine, M. Paxton, W. Versfeld, Breeding data on the birds of Namibia: Laying months, colony and clutch sizes and egg measurements. *Biodivers. Obs.*, 92–196 (2015).
72. K. Isler, C. van Schaik, Costs of encephalization: The energy trade-off hypothesis tested on birds. *J. Hum. Evol.* **51**, 228–243 (2006).
73. P. Langer, Lactation, weaning period, food quality, and digestive tract differentiations in eutheria. *Evolution* **57**, 1196–1215 (2003).
74. C. Schuppli, S. M. Graber, K. Isler, C. P. van Schaik, Life history, cognition and the evolution of complex foraging niches. *J. Hum. Evol.* **92**, 91–100 (2016).

75. U. Roll *et al.*, The global distribution of tetrapods reveals a need for targeted reptile conservation. *Nat. Ecol. Evol.* **1**, 1677–1682 (2017).
76. G. Murali, R. Gumbs, S. Meiri, U. Roll, Global determinants and conservation of evolutionary and geographic rarity in land vertebrates. *Sci. Adv.* **7**, eabe5582 (2021).
77. J. A. Tobias *et al.*, Territoriality, social bonds, and the evolution of communal signaling in birds. *Front. Ecol. Evol.* **4**, 74 (2016).
78. R Core Team, R: A language and environment for statistical computing (Version 4.0.2, R Foundation for Statistical Computing, Vienna, Austria, 2016).
79. W. Revelle, Procedures for psychological, psychometric, and personality research (R Package Version 1.9.12, Evanston, Illinois, 2012).
80. P. A. Murtaugh, Performance of several variable-selection methods applied to real ecological data. *Ecol. Lett.* **12**, 1061–1068 (2009).
81. B. Shipley, Confirmatory path analysis in a generalized multilevel context. *Ecology* **90**, 363–368 (2009).
82. D. Butler, Asreml: Fits the linear mixed model (R package version 4.1.0.110, VSNi, Hemel Hempstead, UK, 2019).