Supplementary Information for
The evolution of brain neuron numbers in amniotes

Kristina Kverková¹, Lucie Marhounová¹, Alexandra Polonyiová¹, Martin Kocourek¹, Yicheng Zhang¹, Seweryn Olkowicz¹, Barbora Straková¹, Zuzana Pavelková¹, Roman Vodička², Daniel Frynta¹, Pavel Němec².

*Corresponding author: Pavel Němec
Email: pgnemec@natur.cuni.cz

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Supplementary Figure 1. Neuron densities go down with increasing brain structure mass across amniotes. Log-log plot of neuron densities against whole brain or brain part mass. The lines represent PGLS regression for the different groups.
Supplementary Figure 2. Brain cellular scaling rules for birds, mammals and non-avian reptiles. (A, B) Scaling of the number of neurons with brain mass. The lines are PGLS regression lines. (C-E) Scaling of the number of neurons with body mass. The lines are PGLS regression lines. (F) Ratio of cerebellar to telencephalic neurons. The line represents a 1:1 ratio.
Supplementary Figure 3. Scaling of brain neurons with brain mass as estimated by bayou analysis for the 251 amniote species.
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Supplementary Figure 5. Scaling of cerebellar neurons with brain mass as estimated by bayou analysis for the 251 amniote species.
Supplementary Figure 6. Scaling of rest of brain neurons with brain mass as estimated by bayou analysis for the 251 amniote species.
Supplementary Figure 7. Shifts in neurons-body scaling in amniotes. (A) Tree colors correspond to neuron numbers relative to body mass, with blue colors indicating low neuron numbers and red colors high neuron numbers. The arrows indicate the branches with shifts in allometric relationship between body mass and neuron number (resulting in either an increase in neurons – arrow up, or a decrease in neurons – arrow down) for the whole brain, telencephalon, cerebellum and rest of brain, identified by reversible-jump Markov chain Monte Carlo analysis with posterior probability > 0.7 for clades including more than 3 species. (B-E) Log-log plots of neuron number for body mass with regression lines for the distinct regimes identified by PGLS analysis.
Supplementary Figure 8. Phenograms showing the evolution of telencephalic and pallial neuron numbers relative to body mass over time. Numbers of telencephalic and pallial neurons relative to body mass in mammals and birds are plotted side by side for comparison. The x-axis is flipped in birds, so that 0 (the present) is in the middle and the axis extends symmetrically left and right.
Supplementary Figure 9. Large relative brain size is positively associated with high relative neuron density within primates. Relative brain size and relative neuron density refer to residuals from regression of neuron density on brain size and brain mass on body mass, respectively. The line is a PGLS regression line for primates.
Supplementary Figure 10. Example of how the fold change in the number of neurons for body mass was calculated.
Table S1. Brain mass and neuron number scaling with body mass for birds, mammals and non-avian reptiles.

| Group         | Intercept±SE | Slope±SE | Mean difference | P-value | Pagel’s λ |
|---------------|--------------|----------|-----------------|---------|-----------|
| **Brain mass ~ Body mass** |              |          |                 |         |           |
| Birds         | -1.125±0.121 | 0.592±0.022 | 7.2x            | <0.001  | 1.049     |
| Mammals       | -1.311±0.191 | 0.686±0.025 | 8.42x           | <0.001  | 0.893     |
| Reptiles      | -1.688±0.102 | 0.503±0.018 | NA              | <0.001  | 0.849     |
| **Brain neurons ~ Body mass** |              |          |                 |         |           |
| Birds         | 7.356±0.15   | 0.439±0.03  | 24.99x          | <0.001  | 0.980     |
| Mammals       | 7.021±0.214  | 0.545±0.028 | 22.82x          | <0.001  | 0.900     |
| Reptiles      | 6.44±0.102   | 0.288±0.018 | NA              | <0.001  | 0.849     |
| **Telencephalon neurons ~ Body mass** |              |          |                 |         |           |
| Birds         | 6.874±0.209  | 0.45±0.041  | 20.02x          | <0.001  | 0.986     |
| Mammals       | 6.613±0.249  | 0.444±0.032 | 9.48x           | <0.001  | 0.909     |
| Reptiles      | 6.01±0.113   | 0.32±0.021  | NA              | <0.001  | 0.811     |
| **Cerebellum neurons ~ Body mass** |              |          |                 |         |           |
| Birds         | 7.072±0.12   | 0.44±0.024  | 51.35x          | <0.001  | 0.974     |
| Mammals       | 6.797±0.219  | 0.574±0.029 | 75.41x          | <0.001  | 0.880     |
| Reptiles      | 5.666±0.225  | 0.326±0.036 | NA              | <0.001  | 0.923     |
| **Rest of brain neurons ~ Body mass** |              |          |                 |         |           |
| Birds         | 6.936±0.107  | 0.19±0.022  | 6.91x           | <0.001  | 0.961     |
| Mammals       | 6.276±0.136  | 0.348±0.022 | 4.27x           | <0.001  | 0.703     |
| Reptiles      | 6.016±0.099  | 0.225±0.018 | NA              | <0.001  | 0.854     |

The scaling coefficients are from PGLS regression of log10-transformed values. The mean difference refers to the difference in trait mean relative to body mass compared to reptiles. NA, "not applicable".
Table S2. Neuron-brain structure scaling rules for the allometric grades identified by PGLS analysis.

| Grade                               | Intercept±SE | Slope±SE     | Pagel's λ | ΔAIC | P-value |
|-------------------------------------|--------------|--------------|-----------|------|---------|
| Brain neurons ~ Brain mass          |              |              |           |      |         |
| Reptiles                            | 7.41±0.075   | 0.602±0.027  | 0.77      | 74   | <0.001  |
| Other birds and mammals             | 8.096±0.098  | 0.751±0.031  |           |      |         |
| Core landbirds and anthropoids      | 8.281±0.107  | 0.820±0.039  |           |      |         |
| Telencephalic neurons ~ Telencephalon mass |              |              |           |      |         |
| Reptiles                            | 7.191±0.085  | 0.613±0.031  | 0.70      | 85   | <0.001  |
| Other birds and mammals             | 7.734±0.111  | 0.613±0.035  |           |      |         |
| Core landbirds and anthropoids      | 8.088±0.119  | 0.783±0.045  |           |      |         |
| Cerebellar neurons ~ Cerebellum mass|              |              |           |      |         |
| Reptiles                            | 7.767±0.137  | 0.693±0.029  | 0.94      | 28   | <0.001  |
| Birds and mammals                   | 8.589±0.172  | 0.844±0.034  |           |      |         |
| Rest of brain neurons ~ Rest of brain mass |              |              |           |      |         |
| Reptiles, marsupials, carnivores and even-toed ungulates | 7.076±0.05 | 0.53±0.022 |           |      |         |
| Other birds                         | 7.539±0.091  | 0.41±0.048   | 0.57      | 46   | <0.001  |
| Placental mammals                   | 7.28±0.048   | 0.623±0.031  |           |      |         |
| Songbirds                           | 7.72±0.105   | 0.511±0.08   |           |      |         |

ΔAIC and p-value refer to the comparison between the best-fit model and the null model (no allometric shifts).
Table S3. Neuron-body scaling rules for the allometric grades identified by PGLS analysis.

| Grade                          | Intercept±SE | Slope±SE | Pagel’s λ | ΔAIC | P-value |
|-------------------------------|--------------|----------|-----------|------|---------|
| **Brain neurons ~ Body mass** |              |          |           |      |         |
| Reptiles                      | 6.446±0.133  | 0.29±0.022 |           | 0.80 | 138     | <0.001  |
| Other birds and mammals       | 7.085±0.175  | 0.498±0.028 |           |      |         |
| Primates                      | 7.705±0.201  | 0.493±0.044 |           |      |         |
| Core landbirds                | 6.626±0.331  | 0.826±0.078 |           |      |         |
| **Telencephalic neurons ~ Body mass** |              |          |           |      |         |
| Reptiles                      | 5.997±0.158  | 0.32±0.026 |           | 0.81 | 114     | <0.001  |
| Other birds and mammals       | 6.705±0.207  | 0.42±0.032 |           |      |         |
| Core landbirds and monkeys    | 7.176±0.231  | 0.571±0.046 |           |      |         |
| **Cerebellum neurons ~ Body mass** |              |          |           |      |         |
| Reptiles                      | 5.591±0.228  | 0.374±0.034 |           | 0.92 | 81      | <0.001  |
| Other birds and mammals       | 6.913±0.295  | 0.507±0.04  |           |      |         |
| Anthropoid primates           | 6.248±0.482  | 0.879±0.102 |           |      |         |
| Snakes                        | 5.365±0.315  | 0.126±0.086 |           |      |         |
| **Rest of brain neurons ~ Body mass** |              |          |           |      |         |
| Reptiles                      | 6.009±0.121  | 0.227±0.02  |           | 0.78 | 66      | <0.001  |
| Birds                         | 6.995±0.193  | 0.185±0.032 |           |      |         |
| Other mammals                 | 6.327±0.206  | 0.327±0.026 |           |      |         |
| Anthropoid primates           | 6.01±0.329   | 0.537±0.071 |           |      |         |

ΔAIC and p-value refer to the comparison between the best-fit model and the null model (no allometric shifts).
Table S4. Neuron-brain structure scaling rules for the allometric grades identified by PGLS analysis in the dataset with imputed data for olfactory bulbs and striatum.

| Grade                                      | Intercept±SE | Slope±SE | Pagel's $\lambda$ | ΔAIC | P-value |
|--------------------------------------------|--------------|----------|-------------------|------|---------|
| **Brain neurons ~ Brain mass**             |              |          |                   |      |         |
| Reptiles                                   | 7.41±0.075   | 0.602±0.027 |                  |      |         |
| Other birds and mammals                    | 8.1±0.091    | 0.751±0.03 | 0.73              | 78   | <0.001  |
| Core landbirds and anthropoids              | 8.287±0.098  | 0.816±0.038 |                  |      |         |
| **Telencephalic neurons ~ Telencephalon mass** |              |          |                   |      |         |
| Reptiles                                   | 7.191±0.085  | 0.613±0.031 |                  |      |         |
| Other birds and mammals                    | 7.743±0.106  | 0.618±0.035 | 0.7               | 87   | <0.001  |
| Core landbirds and anthropoids              | 8.097±0.115  | 0.779±0.044 |                  |      |         |
| **Cerebellar neurons ~ Cerebellum mass**    |              |          |                   |      |         |
| Reptiles                                   | 7.767±0.137  | 0.693±0.029 |                  | 0.94 | 28      | <0.001  |
| Birds and mammals                          | 8.589±0.172  | 0.844±0.034 |                  |      |         |
| **Rest of brain neurons ~ Rest of brain mass** |              |          |                   |      |         |
| Reptiles, marsupials, carnivores and even-toed ungulates | 7.045±0.039 | 0.516±0.022 |                  | 0.32 | 41      | <0.001  |
| Other birds                                | 7.531±0.071  | 0.41±0.053  |                  |      |         |
| Placental mammals                          | 7.243±0.043  | 0.588±0.032 |                  |      |         |
| Songbirds                                  | 7.72±0.105   | 0.511±0.08  |                  |      |         |

ΔAIC and p-value refer to the comparison between the best-fit model and the null model (no allometric shifts).
**Table S5.** Neuron-body scaling rules for the allometric grades identified by PGLS analysis in the dataset with imputed data for olfactory bulbs and striatum.

| Grade | Intercepts±SE | Slope±SE | Pagel’s λ | ΔAIC | P-value |
|-------|---------------|----------|-----------|------|---------|
| **Brain neurons ~ Body mass** | | | | | |
| Reptiles | 6.446±0.133 | 0.29±0.022 | | | |
| Other birds and mammals | 7.072±0.167 | 0.502±0.027 | 0.78 | 146 | <0.001 |
| Primates | 7.707±0.192 | 0.492±0.043 | | | |
| Core landbirds | 6.815±0.257 | 0.783±0.063 | | | |
| **Telencephalic neurons ~ Body mass** | | | | | |
| Reptiles | 6.002±0.157 | 0.32±0.026 | | | |
| Other birds and mammals | 6.727±0.206 | 0.42±0.032 | 0.82 | 115 | <0.001 |
| Core landbirds and anthropoids | 7.196±0.23 | 0.569±0.045 | | | |
| **Cerebellum neurons ~ Body mass** | | | | | |
| Reptiles | 5.591±0.228 | 0.374±0.034 | | | |
| Other birds and mammals | 6.913±0.295 | 0.507±0.04 | 0.92 | 81 | <0.001 |
| Anthropoid primates | 6.248±0.482 | 0.879±0.102 | | | |
| Snakes | 5.365±0.315 | 0.126±0.086 | | | |
| **Rest of brain neurons ~ Body mass** | | | | | |
| Reptiles | 6.007±0.119 | 0.228±0.021 | | | |
| Birds | 7.012±0.191 | 0.181±0.034 | 0.7 | 48.5 | <0.001 |
| Other mammals | 6.275±0.2 | 0.312±0.028 | | | |
| Anthropoid primates | 5.73±0.343 | 0.542±0.078 | | | |

ΔAIC and p-value refer to the comparison between the best-fit model and the null model (no allometric shifts).
Table S6. Comparison of rates of neuron-structure mass evolution in the identified grades. \( \sigma^2 \) indicates the rate of evolution of allometric residuals.

| Group          | \( \sigma^2 \) | Reptiles | Other birds | Other mammals | Primates | Core landbirds |
|----------------|----------------|----------|-------------|---------------|----------|---------------|
| **Brain neurons ~ Brain mass** |               |          |             |               |          |               |
| Reptiles       | 0.0002         | NA       | 0.8         | 0.38***       | 0.26**   | 0.77          |
| Other birds    | 0.0003         | 1.24     | NA          | 0.48*         | 0.32*    | 0.95          |
| Other mammals  | 0.0005         | 2.61***  | 2.1*        | NA            | 0.67     | 2*            |
| Primates       | 0.0008         | 3.91**   | 3.15*       | 1.5           | NA       | 2.99*         |
| Core landbirds | 0.0003         | 1.31     | 1.05        | 0.5*          | 0.33*    | NA            |
| **Telencephalon neurons ~ Telencephalon mass** |               |          |             |               |          |               |
| Reptiles       | 0.0002         | NA       | 0.4**       | 0.22****      | 0.12***  | 0.31****      |
| Other birds    | 0.0005         | 2.48**   | NA          | 0.53          | 0.29*    | 0.77          |
| Other mammals  | 0.0010         | 4.65***  | 1.87        | NA            | 0.55     | 1.45          |
| Primates       | 0.0018         | 8.43***  | 3.4*        | 1.81          | NA       | 2.63          |
| Core landbirds | 0.0007         | 3.21***  | 1.29        | 0.69          | 0.38     | NA            |
| **Cerebellum neurons ~ Cerebellum mass** |               |          |             |               |          |               |
| Reptiles       | 0.0005         | NA       | 2.45**      | 1.77*         | 0.29*    | 2.86***       |
| Other birds    | 0.0002         | 0.41**   | NA          | 0.72          | 0.12***  | 1.17          |
| Other mammals  | 0.0003         | 0.56*    | 1.38        | NA            | 0.16***  | 1.61          |
| Primates       | 0.0016         | 3.49*    | 8.56***     | 6.2***        | NA       | 10.01***      |
| Core landbirds | 0.0002         | 0.35***  | 0.85        | 0.62          | 0.1***   | NA            |
| **Rest of brain neurons ~ Rest of brain mass** |               |          |             |               |          |               |
| Reptiles       | 0.0002         | NA       | 0.46*       | 0.19****      | 0.08***  | 0.73          |
| Other birds    | 0.0004         | 2.2*     | NA          | 0.41**        | 0.17**   | 1.61          |
| Other mammals  | 0.0009         | 5.33***  | 2.43**      | NA            | 0.41     | 3.92***       |
| Primates       | 0.0021         | 13.06*** | 5.94**      | 2.45          | NA       | 9.59***       |
| Core landbirds | 0.0002         | 1.36     | 0.62        | 0.26***       | 0.1***   | NA            |

Values represent ratios between rates of the group in the row and the groups in the columns. NA means "not applicable". Statistically significant differences between groups: ***, p < 0.001; **, p 0.01 – 0.001; *, p 0.01 – 0.05; no symbol, p > 0.05
Table S7. Comparison of rates of neuron-body evolution in the identified grades. \( \sigma^2 \) indicates the rate of evolution of allometric residuals.

| Group | \( \sigma^2 \) | Reptiles | Other birds | Other mammals | Primates | Core landbirds |
|-------|----------------|-----------|-------------|---------------|----------|----------------|
|       | Brain neurons ~ Body mass |           |             |               |          |                |
| Reptiles | 0.0005 | NA | 1.25 | 0.61* | 0.07*** | 0.67 |
| Birds | 0.0004 | 0.8 | NA | 0.49* | 0.06*** | 0.54. |
| Other mammals | 0.0009 | 1.65* | 2.06* | NA | 0.12*** | 1.11 |
| Primates | 0.0077 | 14.13*** | 17.68*** | 8.59*** | NA | 9.52*** |
| Core landbirds | 0.0008 | 1.48 | 1.86. | 0.9 | 0.11*** | NA |
|       | Telencephalon neurons ~ Body mass |           |             |               |          |                |
| Reptiles | 0.0005 | NA | 0.59 | 0.37*** | 0.06*** | 0.31*** |
| Birds | 0.0008 | 1.69. | NA | 0.62 | 0.1*** | 0.53. |
| Other mammals | 0.0013 | 2.73*** | 1.62 | NA | 0.17** | 0.86 |
| Primates | 0.0079 | 16.54*** | 9.70*** | 6.05** | NA | 5.18** |
| Core landbirds | 0.0015 | 3.19*** | 1.89. | 1.17 | 0.19** | NA |
|       | Cerebellum neurons ~ Body mass |           |             |               |          |                |
| Reptiles | 0.0013 | NA | 3.17*** | 1.27 | 0.14*** | 2.37** |
| Birds | 0.0004 | 0.32*** | NA | 0.4** | 0.04*** | 0.75 |
| Other mammals | 0.0010 | 0.79 | 2.49** | NA | 0.11*** | 1.86* |
| Primates | 0.0093 | 7.11*** | 22.54*** | 9.05*** | NA | 16.82*** |
| Core landbirds | 0.0006 | 0.42** | 1.34 | 0.54* | 0.06*** | NA |
|       | Resto of brain neurons ~ Body mass |           |             |               |          |                |
| Reptiles | 0.0003 | NA | 0.6. | 0.28**** | 0.05*** | 0.82 |
| Birds | 0.0005 | 1.67. | NA | 0.47* | 0.08*** | 1.36 |
| Other mammals | 0.0011 | 3.55*** | 2.13* | NA | 0.18** | 2.91*** |
| Primates | 0.0062 | 19.94*** | 11.96*** | 5.61** | NA | 16.32*** |
| Core landbirds | 0.0004 | 1.22 | 0.73 | 0.34*** | 0.06*** | NA |

Values represent ratios between rates of the group in the row and the groups in the columns. NA means "not applicable". Statistically significant differences between groups: ***, p < 0.001; **, p 0.01 – 0.001; *, p 0.01 – 0.05; no symbol, p > 0.05.
Table S8. Comparison of rates of neuron-structure mass evolution of different brain structures in non-avian reptiles, birds and mammals.

| Structure       | \( \sigma^2 \) | Telencephalon | Cerebellum | Rest of brain |
|-----------------|----------------|--------------|------------|---------------|
| **Reptiles**    |                |              |            |               |
| Telencephalon   | 0.0011         | NA           | 0.35***    | 1.45          |
| Cerebellum      | 0.0003         | 2.86***      | NA         | 4.15***       |
| Rest of brain   | 0.0004         | 0.69         | 0.24***    | NA            |
| **Birds**       |                |              |            |               |
| Telencephalon   | 0.0004         | NA           | 2.93***    | 3.56***       |
| Cerebellum      | 0.0003         | 0.34***      | NA         | 1.21          |
| Rest of brain   | 0.0012         | 0.28***      | 0.82       | NA            |
| **Mammals**     |                |              |            |               |
| Telencephalon   | 0.0021         | NA           | 1.1        | 1.32          |
| Cerebellum      | 0.0017         | 0.91         | NA         | 1.2           |
| Rest of brain   | 0.0023         | 0.75         | 0.83       | NA            |

\( \sigma^2 \) indicates the rate of evolution of allometric residuals. Values represent ratios between rates for the structure in the row and the structures in the columns. NA means “not applicable”. Statistically significant differences between groups: ***, \( p < 0.001 \); **, \( p 0.01 – 0.001 \); *, \( p 0.01 – 0.05 \); no symbol, \( p > 0.05 \).
Dataset S1 (separate file). Numbers of neurons and non-neuronal cells in the investigated brain parts for 145 species of birds and non-avian reptiles.

Dataset S2 (separate file). Brain and body masses for 149 species of non-avian reptiles.