Electronic supplementary material

Cellular scaling rules for brains of the galliform birds (Aves, Galliformes) compared to those of songbirds and parrots: Distantly related avian lineages have starkly different neuronal cerebrotypes

Martin Kocourek, Yicheng Zhang, Lucie Marhounová, Patrik Stehlík, Alexandra Polonyiová, Seweryn Olkowicz, Barbora Straková, Zuzana Pavelková, Tomáš Hájek, Tomáš Kušta, Radek K. Lučan, Kristina Kverková and Pavel Němec

Address for correspondence:

Pavel Němec
Department of Zoology
Charles University
Viničná 7
CZ-128 44 Praha 2
Czech Republic
Phone: ++420 2 2195 1855
E-mail: pgnemec@natur.cuni.cz

Content:

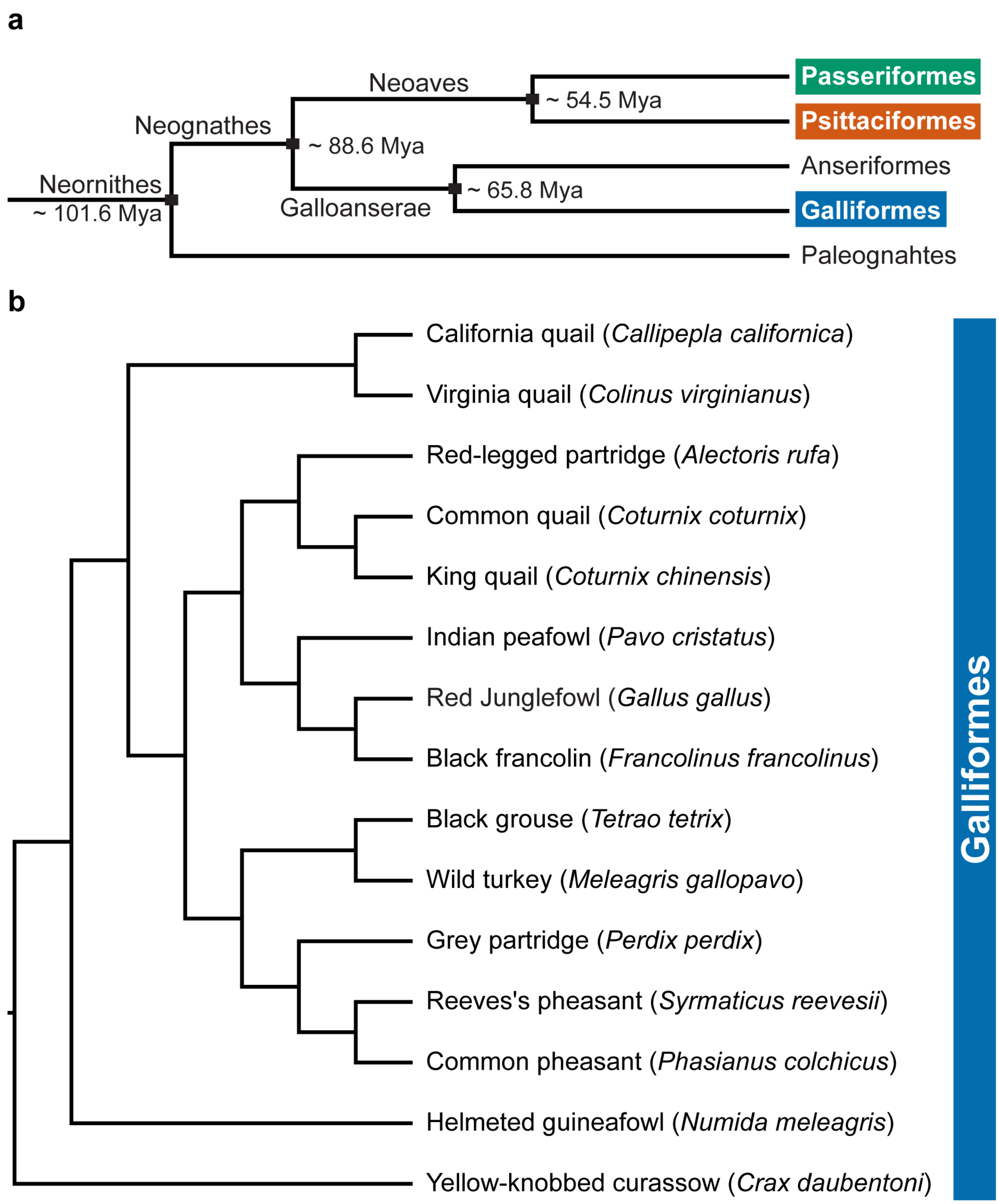

Fig. S1. Phylogenetic relationships of avian taxa analyzed. (a) Relationships between major avian clades, in which scaling rules are compared. Estimated times of divergence of avian lineages are indicated, according to Prum et al. (2015). Note that galliform birds form together with anseriform birds the Galloanseres, a sister group of Neoaves (including all other extant birds except the tinamous and flightless ratites) and the most basal clade of Neognathae. By contrast, songbirds and parrots are sister groups belonging to the Australaves, a crown group of Neoaves. The color code identifying clades is used throughout the figures. **(b)** Relationships among the 15 galliform species examined. The trees were constructed using http://www.birdtree.org, their topologies follow recent studies [21,22].

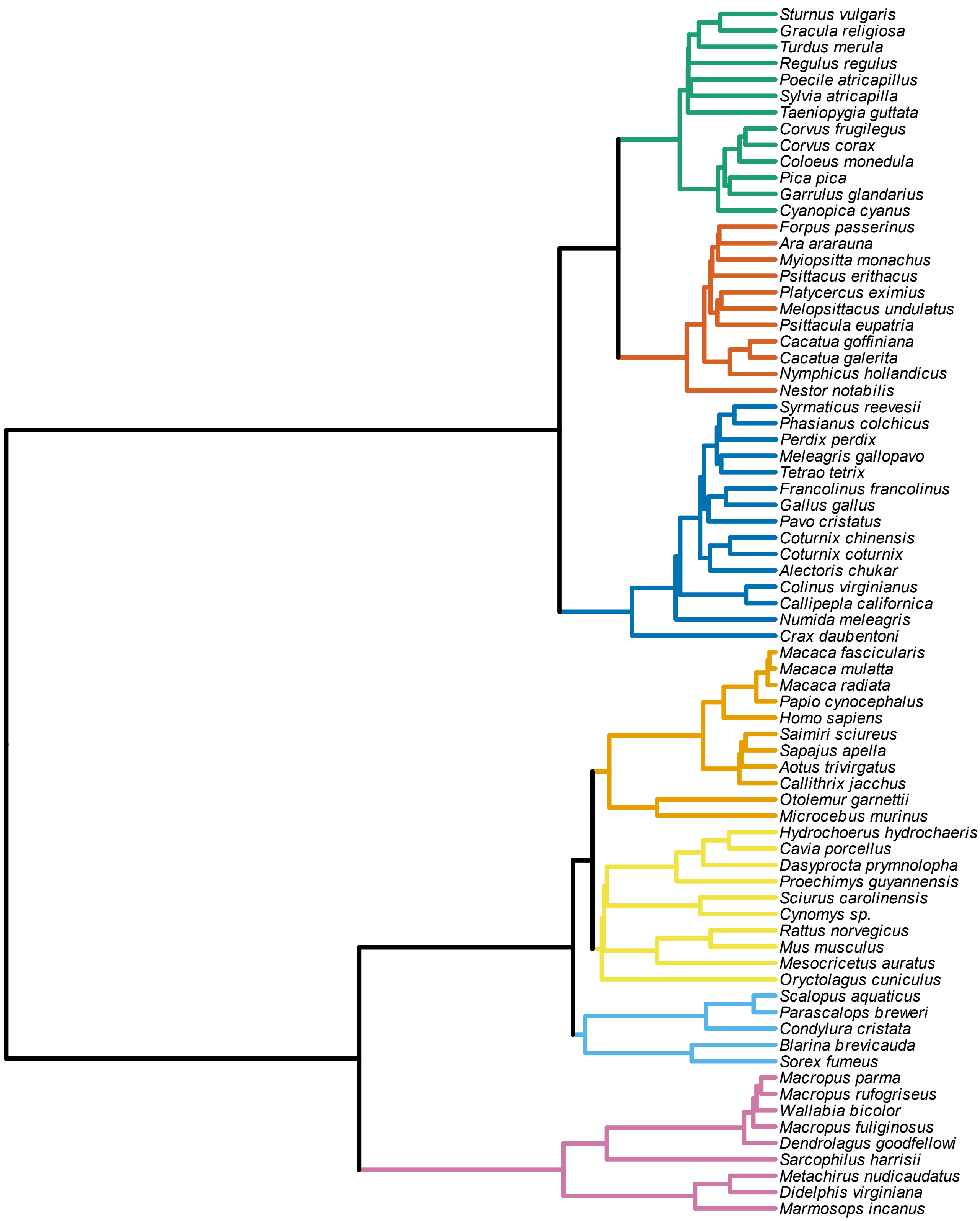

Figure S2. The composite, time-calibrated tree used for phylogenetically informed analyses. Code:
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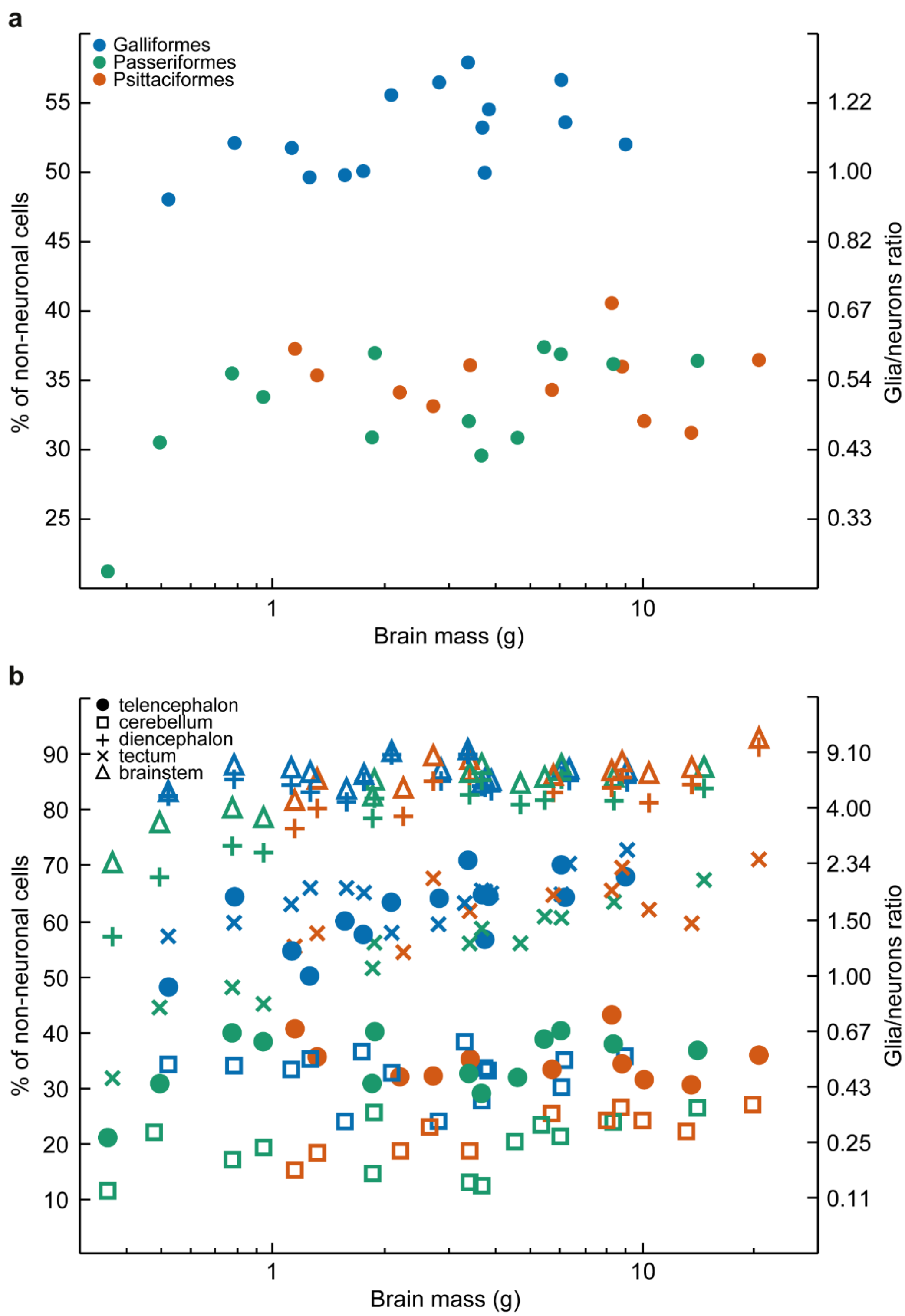

Fig. S3. Glia/neuron ratios for the avian species examined. Each point represents the average proportion of nonneuronal cells (left axis) and the glia/neuron ratio (right axis) for one species, plotted against the average brain mass for that species. Galliform birds are shown in brown, songbirds in green, and parrots in red. **(a)** The overall glia/neuron ratio in the brain. Note the higher proportion of nonneuronal cells in galliform birds. **(b)** Variation in the glia/neuron ratio among the principal brain divisions investigated. Note that galliform birds have distinctly higher proportion of nonneuronal cells in the cerebellum and the telencephalon compared to songbirds and parrots. Also note the high proportion of nonneuronal cells in the brainstem and the diencephalon.

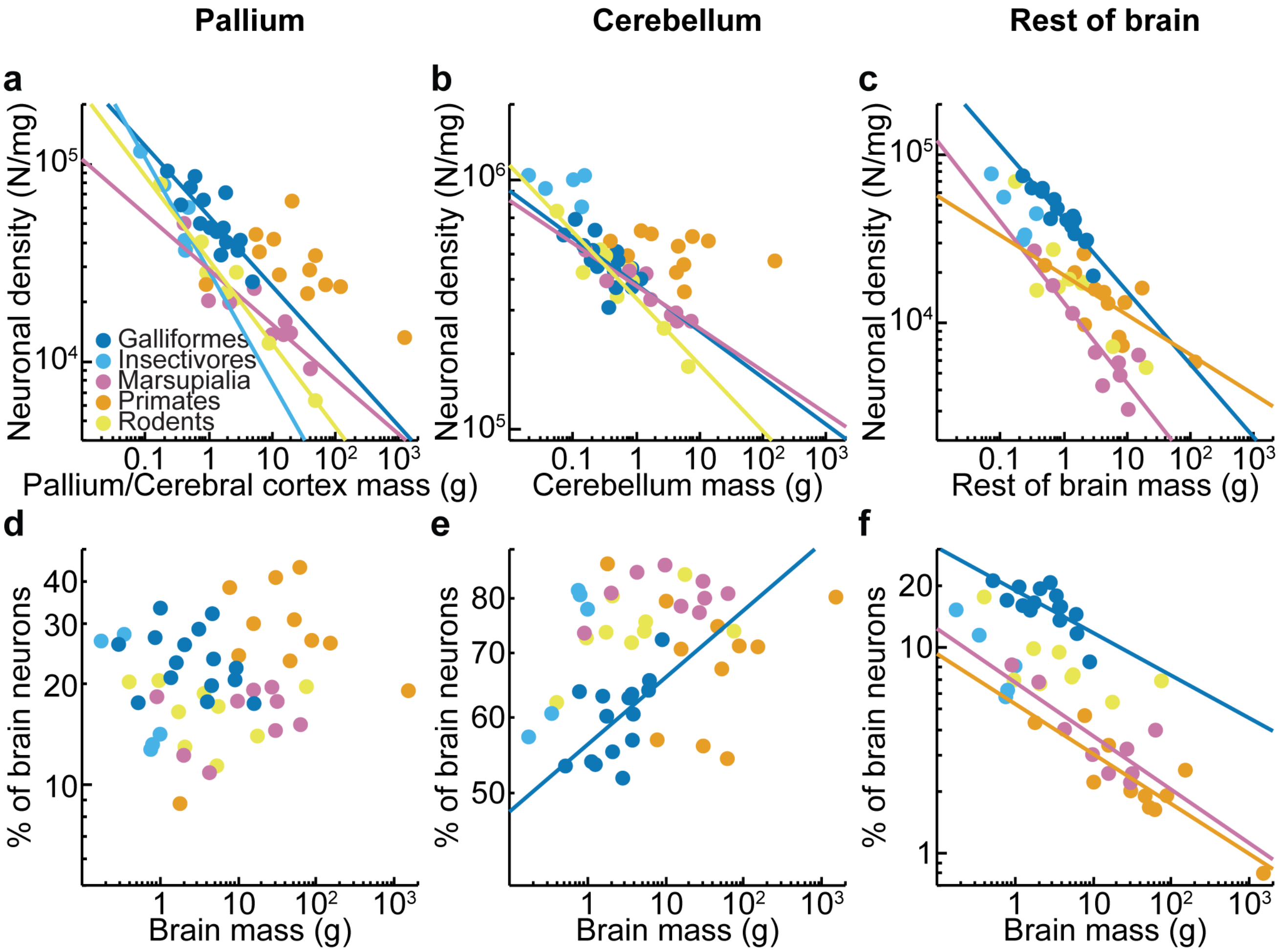

Fig. S4. Neuronal densities and relative distribution of neurons in birds and mammals. (a–c) Neuronal densities in the pallium **(a)**, cerebellum **(b)** and rest of the brain **(c)**. Pallial neuronal densities of galliform birds are not significantly different from those of mammals (PGLS: slopes and intercepts $p > 0.05$ in all cases, but there is a trend towards a higher slope in primates: $t_{50} = 1.967$, $p = 0.056$; $\lambda = 0.86$). Cerebellar neuronal densities in galliforms are comparable to rodents and marsupials, but primates have a higher slope (PGLS: slope = 0.150 ± 0.060, $t_{50} = 2.500$, $p = 0.017$, $\lambda = 0.02$) and insectivores a higher intercept (PGLS: intercept = 0.340 ± 0.011, $t_{50} = 3.081$, $p = 0.004$). Neuronal densities in the rest of brain scale with a higher intercept in galliforms than in marsupials, rodents and primates (PGLS: $p < 0.001$ in all cases, $\lambda = 0.02$). **(d–f)** Average proportions of neurons contained in the pallium **(d)**, cerebellum **(e)** and rest of the brain **(f)**. Note that proportion of brain neurons contained in the rest of brain is higher in galliforms than in mammals. The fitted lines represent OLS regressions and are shown only for correlations that are significant (r^2 ranges between 0.352 and 0.955, $p \leq 0.020$ in all cases). Data for mammals are from published reports (for details, see Methods).

Supplementary Table S1. Cellular composition of the brains of fifteen gallinaceous bird species

Species	n	Body mass [g]	Brain mass [g]	Total neurons [x 10^6]	Total nonneurons [x 10^6]
King quail	3	43.8 ± 2.9	0.521 ± 0.026	80.48 ± 5.42	74.44 ± 5.57
Common quail	3	94.9 ± 14.0	0.787 ± 0.025	117.76 ± 2.12	128.19 ± 3.02
Virginia quail	3	181.1 ± 12.1	1.124 ± 0.100	148.40 ± 13.35	159.20 ± 15.69
California quail	1	199.6	1.256	172.39	169.93
Grey partridge	3	337.3 ± 16.2	1.565 ± 0.035	170.29 ± 22.06	168.91 ± 27.98
Black francolin	2	368.6 ± 11.2	1.755 ± 0.157	232.54 ± 9.34	233.36 ± 19.28
Red-legged partridge	3	459.7 ± 59.1	2.091 ± 0.070	197.18 ± 9.30	246.66 ± 11.71
Red Junglefowl	3	861.3 ± 107.3	2.819 ± 0.200	220.84 ± 44.50	286.68 ± 17.35
Black grouse	2	897.8 ± 192.2	3.375 ± 0.199	280.87 ± 1.96	386.68 ± 43.14
Reeves's pheasant	3	1,119.0 ± 166.6	3.691 ± 0.590	387.17 ± 84.08	440.67 ± 83.70
Helmeted guineafowl	3	1,722.0 ± 276.4	3.747 ± 0.345	447.12 ± 58.43	446.56 ± 52.89
Common pheasant	3	1,221.7 ± 280.3	3.845 ± 0.402	321.36 ± 35.34	385.54 ± 8.86
Wild turkey	3	3,453.6 ± 555.4	6.041 ± 0.468	492.87 ± 13.52	644.29 ± 47.18
Indian peafowl	3	3,599.2 ± 707.2	6.194 ± 0.414	570.93 ± 31.59	659.70 ± 16.86
Yellow-knobbed curassow	1	2,448.6	9.020	652.99	707.84
Variation, max./min.		82.2×	17.3×	8.1×	9.5×

Species ordered by increasing brain size. All values are given as mean ± SD; n, number of individuals analysed.

Supplementary Table S2. Mass of the major brain divisions of fifteen gallinaceous bird species

Species	Telencephalon [g]	Subpallium [% of Tel]	Diencephalon [g]	Tectum [g]	Cerebellum [g]	Brainstem [g]
King quail	0.271 ± 0.014	21.66	0.046 ± 0.002	0.068 ± 0.004	0.070 ± 0.002	0.060 ± 0.004
Common quail	0.417 ± 0.015	14.72	0.077 ± 0.005	0.112 ± 0.005	0.114 ± 0.014	0.084 ± 0.001
Virginia quail	0.605 ± 0.075	17.52	0.107 ± 0.013	0.151 ± 0.014	0.152 ± 0.003	0.126 ± 0.005
California quail	0.699	15.21	0.109	0.145	0.199	0.117
Grey partridge	0.852 ± 0.012	15.40	0.151 ± 0.004	0.191 ± 0.009	0.203 ± 0.013	0.155 ± 0.003
Black francolin	0.983 ± 0.102	19.15	0.164 ± 0.000	0.246 ± 0.041	0.233 ± 0.008	0.162 ± 0.015
Red-legged partridge	1.208 ± 0.065	14.41	0.184 ± 0.013	0.253 ± 0.008	0.248 ± 0.007	0.216 ± 0.009
Red Junglefowl	1.567 ± 0.162	14.83	0.245 ± 0.014	0.345 ± 0.022	0.369 ± 0.024	0.293 ± 0.010
Black grouse	1.841 ± 0.117	17.91	0.310 ± 0.029	0.416 ± 0.005	0.487 ± 0.000	0.342 ± 0.020
Reeves's pheasant	2.039 ± 0.316	19.91	0.300 ± 0.040	0.469 ± 0.091	0.513 ± 0.099	0.326 ± 0.083
Helmeted guineafowl	2.176 ± 0.208	17.53	0.311 ± 0.036	0.407 ± 0.043	0.471 ± 0.086	0.346 ± 0.028
Common pheasant	2.248 ± 0.230	18.46	0.329 ± 0.063	0.466 ± 0.081	0.464 ± 0.059	0.386 ± 0.067
Wild turkey	3.382 ± 0.309	17.11	0.471 ± 0.023	0.662 ± 0.070	0.815 ± 0.037	0.582 ± 0.051
Indian peafowl	3.743 ± 0.252	18.82	0.453 ± 0.023	0.622 ± 0.037	0.872 ± 0.092	0.556 ± 0.031
Yellow-knobbed curassow	5.761	17.16	0.622	0.885	1.302	0.776
Variation, max./min.	21.3×		13.5×	13.0×	18.6×	12.9×

Species ordered by increasing brain size. All values are given as mean ± SD.

Supplementary Table S3. Number of neurons in the major brain divisions of fifteen gallinaceous bird species

Species	Telencephalon [x 10^6]	Subpallium [% of Tel]	Diencephalon [x 10^6]	Tectum [x 10^6]	Cerebellum [x 10^6]	Brainstem [x 10^6]
King quail	25.27 ± 2.62	23.15	1.46 ± 0.12	9.42 ± 1.22	42.95 ± 1.70	1.37 ± 0.16
Common quail	26.75 ± 1.87	18.54	2.26 ± 0.49	11.72 ± 0.19	75.20 ± 2.01	1.83 ± 0.13
Virginia quail	47.37 ± 3.36	21.11	2.77 ± 0.30	16.05 ± 1.37	80.02 ± 10.62	2.19 ± 0.45
California quail	62.00	18.12	3.50	12.61	92.32	1.95
Grey partridge	43.64 ± 12.56	18.31	3.21 ± 0.76	13.48 ± 1.08	107.55 ± 8.56	2.41 ± 0.07
Black francolin	63.80 ± 10.45	17.70	4.16 ± 0.76	22.19 ± 4.09	139.93 ± 4.62	2.45 ± 0.17
Red-legged partridge	58.65 ± 8.33	16.86	3.55 ± 0.20	22.63 ± 1.50	108.89 ± 4.70	3.46 ± 0.22
Red Junglefowl	73.79 ± 2.46	42233	4.02 ± 0.76	25.50 ± 3.26	114.45 ± 39.59	3.08 ± 0.57
Black grouse	64.30 ± 11.47	18.90	5.49 ± 1.14	29.52 ± 2.99	176.65 ± 17.50	4..91 ± 0.06
Reeves's pheasant	98.47 ± 20.68	22.04	5.23 ± 0.46	32.92 ± 7.19	245.72 ± 55.82	4.83 ± 0.20
Helmeted guineafowl	156.62 ± 28.22	18.24	5.16 ± 0.54	27.57 ± 1.11	253.93 ± 28.94	3.84 ± 0.62
Common pheasant	93.11 ± 4.70	22.06	4.72 ± 0.87	25.97 ± 0.84	194.34 ± 36.64	3.23 ± 0.30
Wild turkey	128.33 ± 16.50	21.46	6.12 ± 0.95	37.50 ± 1.36	315.74 ± 25.31	5.17 ± 0.18
Indian peafowl	155.59 ± 13.81	20.04	5.54 ± 0.58	31.31 ± 0.68	374.52 ± 21.71	3.97 ± 0.42
Yellow-knobbed curassow	147.23	18.14	5.43	24.42	472.68	3.24
Variation, max./min.	6.2×		4.2×	4.0×	11.0×	3.8×

Species ordered by increasing brain size. All values are given as mean ± SD.

Supplementary Table S4. Number of nonneuronal cells in the brain divisions of fifteen gallinaceous bird species

Species	Telencephalon [x 10^6]	Subpallium [% of Tel]	Diencephalon [x 10^6]	Tectum [x 10^6]	Cerebellum [x 10^6]	Brainstem [x 10^6]
King quail	23.54 ± 2.96	23.17	8.65 ± 1.01	10.97 ± 1.53	22.59 ± 1.01	8.69 ± 0.66
Common quail	48.42 ± 2.36	18.44	12.73 ± 0.77	19.92 ± 0.76	33.61 ± 3.31	13.52 ± 0.52
Virginia quail	57.20 ± 4.82	21.15	17.97 ± 2.01	23.83 ± 2.50	39.95 ± 4.71	20.25 ± 3.49
California quail	62.50	18.56	19.50	21.63	50.33	15.98
Grey partridge	65.64 ± 20.23	18.32	20.79 ± 4.04	27.75 ± 1.69	34.37 ± 4.06	20.35 ± 1.40
Black francolin	86.83 ± 11.85	17.93	28.71 ± 1.83	36.66 ± 7.23	62.01 ± 0.75	19.16 ± 2.78
Red-legged partridge	101.77 ± 13.22	17.01	30.88 ± 1.91	35.54 ± 2.50	46.11 ± 2.86	32.37 ± 3.64
Red Junglefowl	131.98 ± 9.48	17.00	38.42 ± 4.70	45.39 ± 7.09	28.28 ± 9.67	42.63 ± 0.98
Black grouse	157.14 ± 33.44	19.03	48.15 ± 14.02	50.60 ± 4.73	83.36 ± 11.01	47. 44 ± 1.96
Reeves's pheasant	181.04 ± 38.34	22.04	48.58 ± 8.18	66.85 ± 15.47	95.19 ± 15.14	49.01 ± 7.97
Helmeted guineafowl	205.65 ± 33.11	19.20	46.25 ± 2.70	55.35 ± 2.32	95.47 ± 13.47	43.85 ± 4.59
Common pheasant	169.31 ± 1.08	22.15	47.32 ± 8.10	55.02 ± 1.77	69.94 ± 10.30	43.95 ± 0.18
Wild turkey	301.58 ± 38.07	21.85	71.36 ± 3.06	83.86 ± 1.53	110.20 ± 6.40	77.29 ± 12.14
Indian peafowl	280.56 ± 20.54	20.92	68.36 ± 8.37	89.15 ± 3.16	147.75 ± 1.46	73.88 ± 10.33
Yellow-knobbed curassow	313.17	18.90	63.37	81.40	192.52	57.36
Variation, max./min.	13.3×		8.3×	8.1×	8.5×	8.9×

Species ordered by increasing brain size. All values are given as mean ± SD.

Supplementary Table S5. Cellular scaling rules for brains of gallinaceous birds

Dependent variable	Independent variable	Power law	r^2	p value (exponent)	95 % confidence interval
M_{BR}	N_{BR}	$M_{BR} = 2.939 \times 10^{-11} \times N_{BR}^{1.299}$	0.953	<0.000 1	1.125 - 1.472
M_{TEL}	N_{TEL}	$M_{TEL} = 2.890 \times 10^{-11} \times N_{TEL}^{1.359}$	0.876	<0.000 1	1.052 - 1.665
M_{DIE}	N_{DIE}	$M_{DIE} = 6.377 \times 10^{-13} \times N_{DIE}^{1.745}$	0.899	<0.000 1	1.395 - 2.096
M_{TEC}	N_{TEC}	$M_{TEC} = 8.484 \times 10^{-13} \times N_{TEC}^{1.574}$	0.850	<0.000 1	1.178 - 1.970
M_{CB}	N_{CB}	$M_{CB} = 9.728 \times 10^{-11} \times N_{CB}^{1.164}$	0.945	<0.000 1	0.996 - 1.331
M_{BS}	N_{BS}	$M_{BS} = 3.791 \times 10^{-12} \times N_{BS}^{1.667}$	0.772	<0.000 1	1.124 - 2.211
M_{BR}	O_{BR}	$M_{BR} = 1.593 \times 10^{-10} \times O_{BR}^{1.204}$	0.979	<0.000 1	1.098 - 1.311
M_{TEL}	O_{TEL}	$M_{TEL} = 1.707 \times 10^{-9} \times O_{TEL}^{1.104}$	0.972	<0.000 1	0.993 - 1.216
M_{DIE}	O_{DIE}	$M_{DIE} = 6.733 \times 10^{-10} \times O_{DIE}^{1.130}$	0.979	<0.000 1	1.030 - 1.229
M_{TEC}	O_{TEC}	$M_{TEC} = 3.362 \times 10^{-10} \times O_{TEC}^{1.175}$	0.979	<0.000 1	1.072 - 1.277
M_{CB}	O_{CB}	$M_{CB} = 4.283 \times 10^{-10} \times O_{CB}^{1.140}$	0.797	<0.000 1	0.795 - 1.484
M_{BS}	O_{BS}	$M_{BS} = 1.092 \times 10^{-9} \times O_{BS}^{1.112}$	0.957	<0.000 1	0.971 - 1.252

Power laws were calculated from the average species values listed in Tables S1–S4. BR, Brain; BS, brainstem; CB, cerebellum; DIE, diencephalon; M, mass (in grams); N, number of neurons; O, number of other (nonneuronal) cells; r^2, coefficient of determination calculated from the ordinary least squares regression of species averages; TEC, tectum; TEL, telencephalon.

List of references to Figure 4. Brain-body scaling in birds and mammals.
The data on body mass and brain mass were collated from the literature listed below.

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