

**The internal cranial anatomy of *Champsosaurus* (Choristodera: Champsosauridae):
Implications for neurosensory function**

Thomas W. Dudgeon^{1*}, Hillary C. Maddin¹, David C. Evans^{2,3}, Jordan C. Mallon^{1,4}

1 Department of Earth Sciences, Carleton University, Ottawa, Canada;

2 Vertebrate Palaeontology, Royal Ontario Museum, Toronto, Canada;

3 Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, Canada;

4 Beaty Centre for Species Discovery and Palaeobiology Section, Canadian Museum of Nature, Ottawa, Canada.

* Corresponding author thomasdudgeon@cmail.carleton.ca

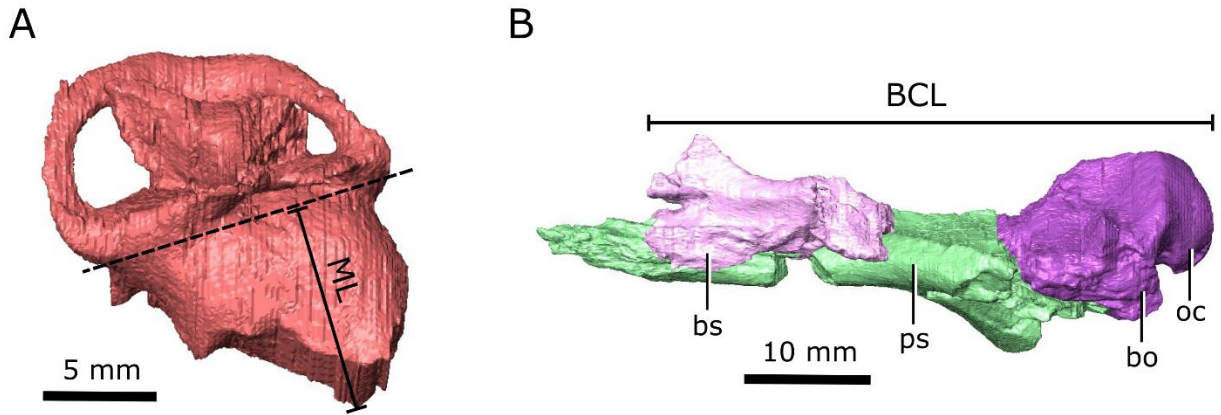


Figure S1: Measurements used for the estimation of auditory capabilities. **A** maximum endocochlear duct length (ML); **B** basicranial length (BCL). *Abbreviations: bo, basioccipital; bs, basisphenoid; oc, occipital condyle; ps, parasphenoid.* Images generated in Amira 5.4.3 (<https://www.fei.com/software/amira/>) and processed in Inkscape 0.92 (<https://inkscape.org/>).

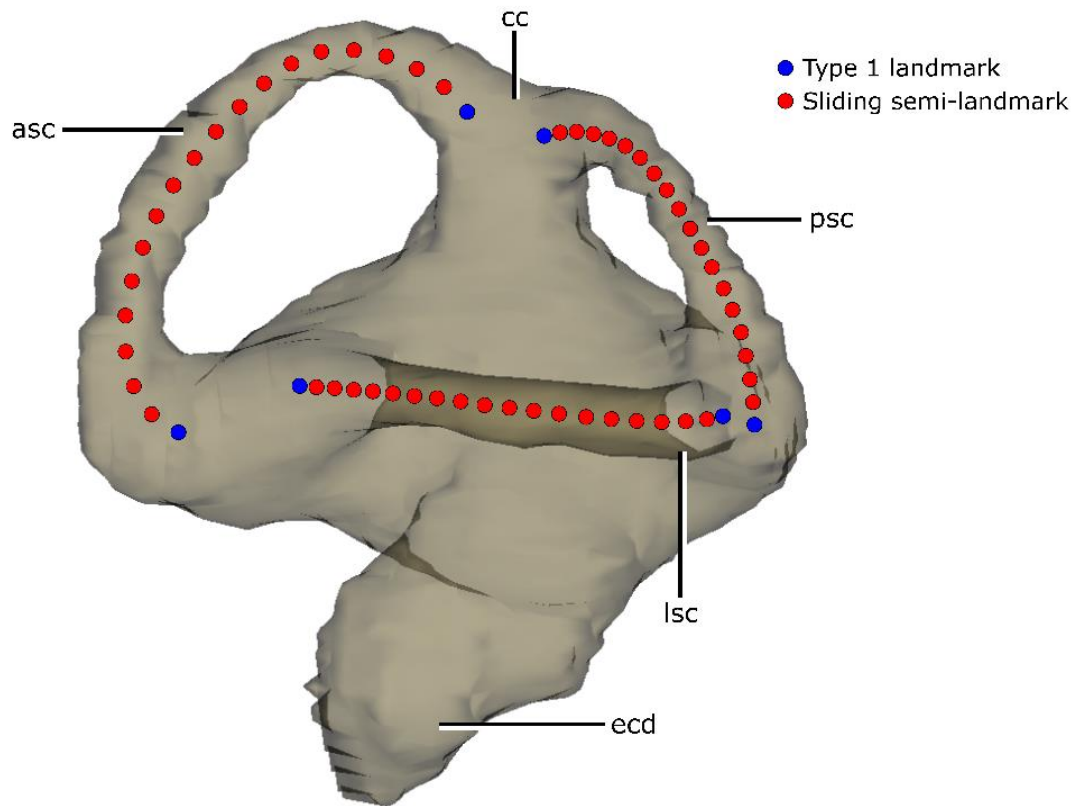


Figure S2: Landmark locations for the three semicircular canals of *Tomistoma schegelii*. Abbreviations: *asc*, anterior semicircular canal; *cc*, crus communis; *ecd*, endocochlear duct; *lsc*, lateral semicircular canal; *psc*, posterior semicircular canal. Image generated in MorphoDig 1.4.0 (<https://morphomuseum.com/morphodig>) and processed in Inkscape 0.92 (<https://inkscape.org/>).

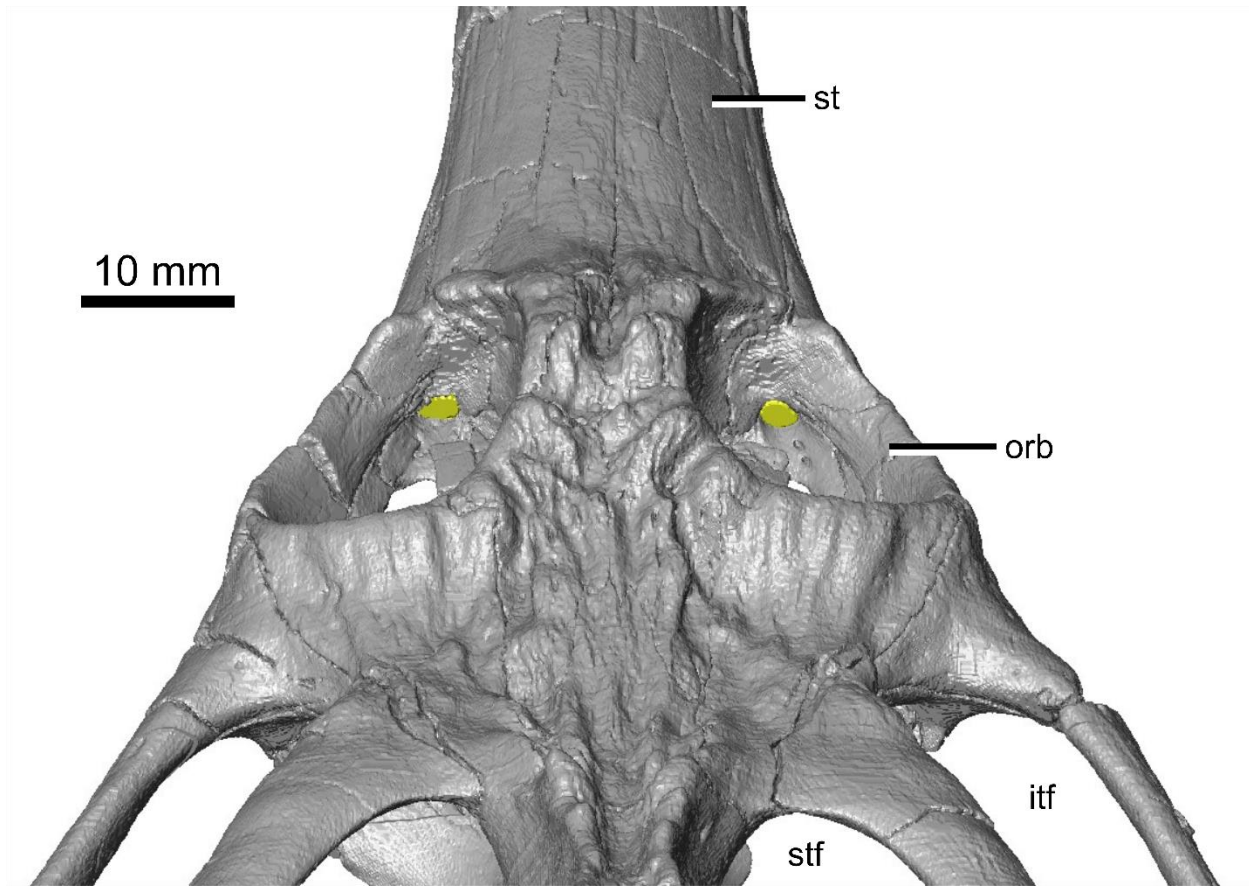


Figure S3: Posterodorsal view of the orbital region of the digitized skull of *Champsosaurus lindoei* (CMN 8920). The canal for the maxillary branch of the trigeminal nerve is visualized in yellow. Abbreviations: *itf*, infratemporal fenestra; *orb*, orbit; *st*, snout; *stf*, supratemporal fenestra. Image generated in Amira 5.4.3 (<https://www.fei.com/software/amira/>).

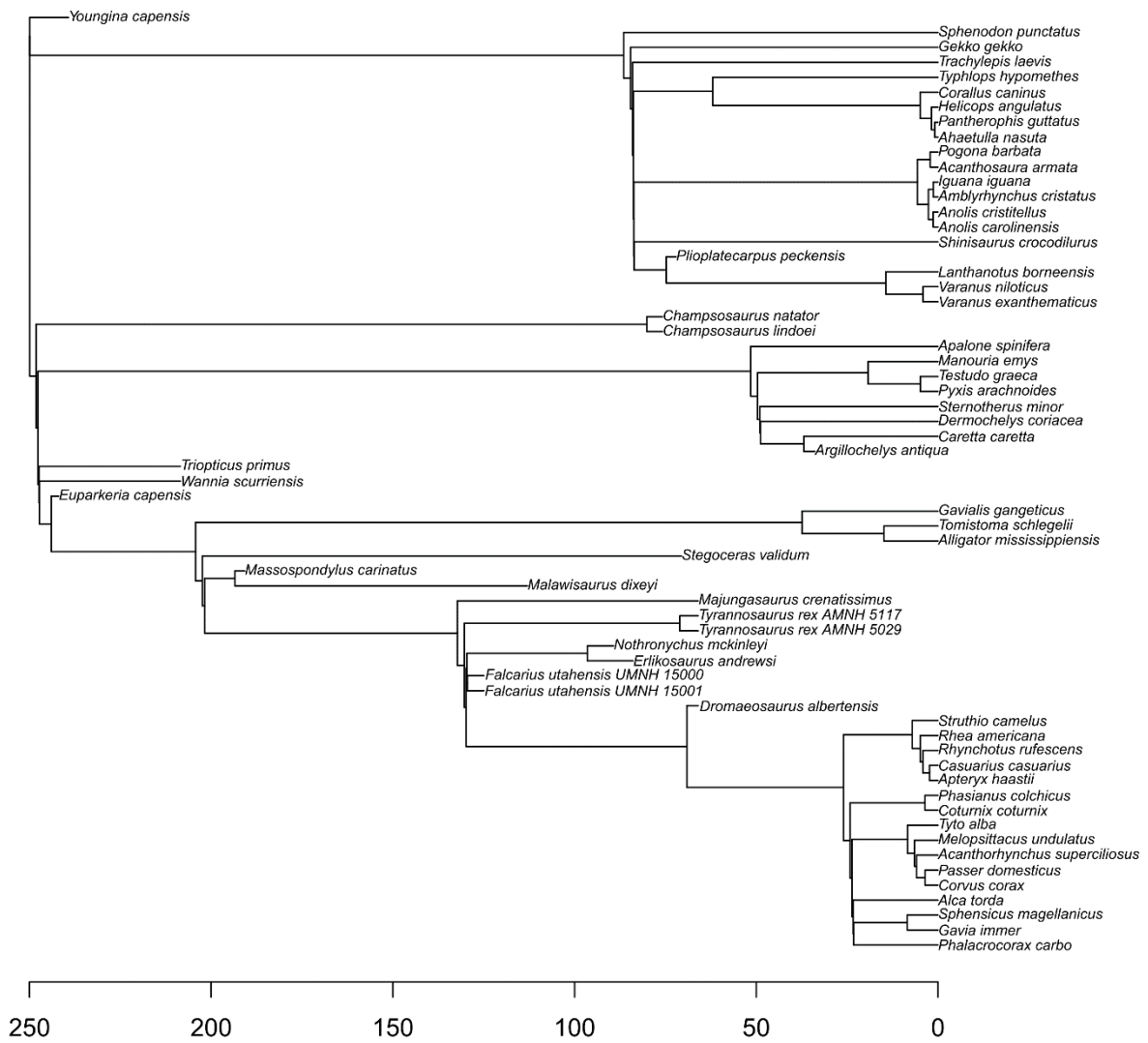


Figure S4: Consensus time-calibrated phylogeny of taxa used in the PCA. Scale bar indicates millions of years before present. Image generated in RStudio 1.2.5019 (<https://rstudio.com/>).

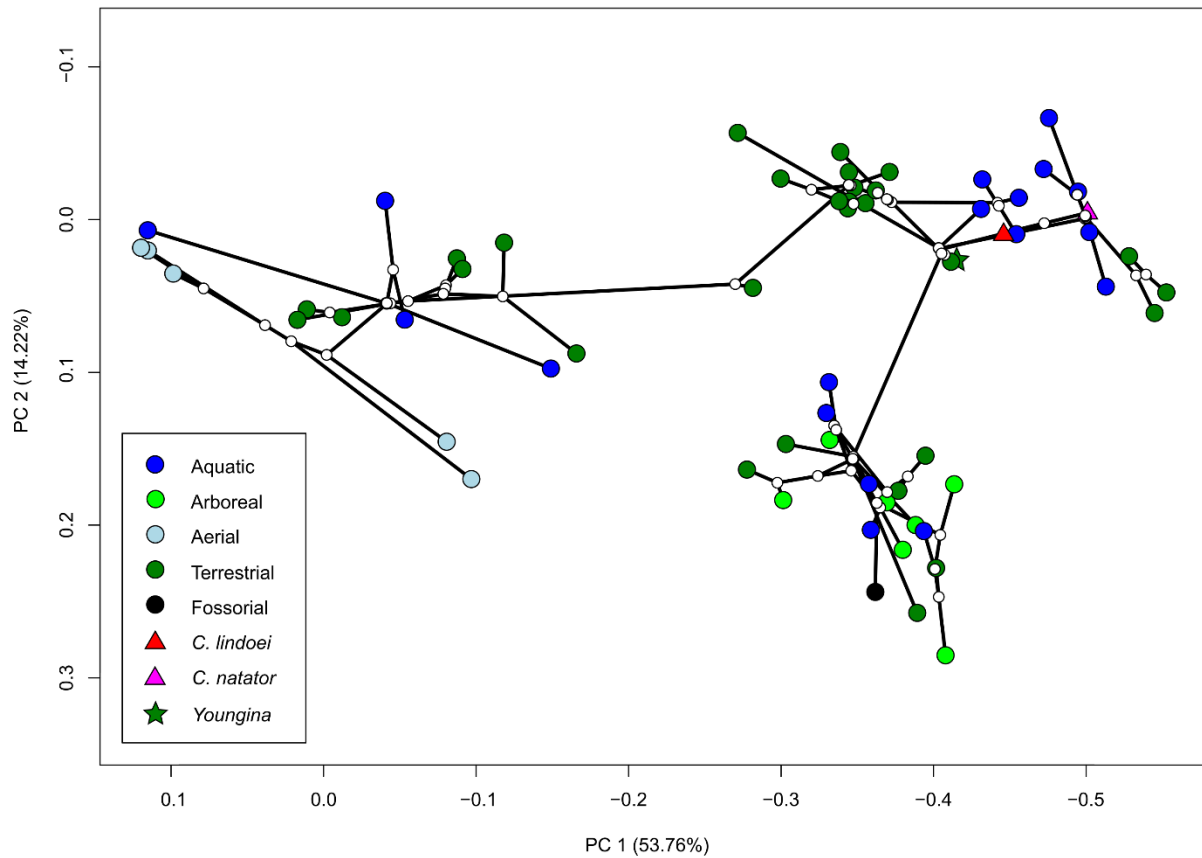


Figure S5: Consensus time-calibrated phylogeny (Supplementary Fig. S4) of included taxa projected into the morphospace of PC1 and PC2. Taxa are colour coded based on ecology. It should be noted that projecting the phylogeny onto PC1 vs PC2 resulted in the PC scores being flipped along PC2; however, this PCA was created solely for visualization of the phylogeny in morphospace and the resulting PC scores were not used in the subsequent analyses. Therefore, the flipping of the PC scores along PC2 in Supplementary Fig. S4 does not influence the results of this study.

Table S1: Bloomberg's K value and associated p-value for both centroid size and landmark coordinates of the endosseous labyrinths. Bloomberg's multivariate K statistic calculated using 1000 permutations. Bold indicates significance (alpha = 0.025).

| | K _{mult} statistic | p-value |
|---------------------|-----------------------------|--------------|
| Centroid Size | 0.1793 | 0.007 |
| Coordinates (shape) | 0.1496 | 0.001 |

Table S2: ANCOVA of ecology, centroid size, and the interaction between ecology and centroid size against canal shape. Bold indicates significance ($\alpha = 0.0166$). Abbreviations: *d.f.*, degrees of freedom; *F*, *F* statistic; *MS*, mean square; *R*², coefficient of determination; *SS*, sum of squares; *Z*, *Z* score.

| | d.f. | SS | MS | R ² | F | Z | p-value |
|----------------------|------|--------|----------|----------------|--------|--------|---------------|
| Ecology | 4 | 0.9649 | 0.241217 | 0.25979 | 5.2177 | 4.3913 | 0.0004 |
| Centroid | 1 | 0.1610 | 0.160951 | 0.04334 | 3.4815 | 2.8402 | 0.0045 |
| Ecology: Centroid | 3 | 0.0918 | 0.030585 | 0.02470 | 0.6616 | 0.0787 | 0.4539 |
| Residuals | 54 | 2.4965 | 0.046231 | 0.67217 | | | |
| Total | 62 | 3.7140 | | | | | |

Table S3: Phylogenetic generalized least squares of semicircular canal shape against ecology, and semicircular canal centroid size. Bold indicates significance ($\alpha = 0.0166$). *Abbreviations: d.f., degrees of freedom; F, F statistic; MS, mean square; R², coefficient of determination; SS, sum of squares; Z, Z score.*

| | d.f. | SS | MS | R ² | F | Z | p-value |
|----------------------|------|----------|-----------|----------------|--------|--------|---------------|
| Ecology | 4 | 0.034176 | 0.0085440 | 0.21451 | 4.3885 | 2.8928 | 0.0173 |
| Centroid | 1 | 0.004592 | 0.0045921 | 0.02882 | 2.3587 | 2.4911 | 0.0065 |
| Ecology: Centroid | 3 | 0.015424 | 0.0051413 | 0.09681 | 2.6408 | 3.0154 | 0.0026 |
| Residuals | 54 | 0.105132 | 0.0019469 | 0.65986 | | | |
| Total | 62 | 0.159324 | | | | | |

Table S4: Posterior probabilities (10 000 permutations) of significant differences between the ecological groups based on Mahalanobis distances. Bold indicates significance ($\alpha = 0.0083$).

| | Aquatic | Aerial | Arboreal | Terrestrial |
|-------------|---------------|---------------|---------------|---------------|
| Aquatic | - | 0.0001 | 0.0009 | 0.0002 |
| Aerial | 0.0001 | - | 0.0001 | 0.0001 |
| Arboreal | 0.0009 | 0.0001 | - | 0.0017 |
| Terrestrial | 0.0002 | 0.0001 | 0.0017 | - |

Table S5: Posterior probabilities (10 000 permutations) and log-likelihood estimations of *Champsosaurus* species belonging to separate ecological groups. Bold indicates significance ($\alpha = 0.00625$). Posterior probabilities less than alpha suggest that *Champsosaurus* is significantly different from that ecological group.

| | | Log-likelihood | Posterior probability | | | |
|------------------------------|--------------------|----------------|-----------------------|-----------------|-----------------|-----------------|
| | | | Aquatic | Aerial | Arboreal | Terrestrial |
| <i>Champsosaurus lindoei</i> | Aquatic (0.969) | 0.820 | | < 0.0001 | < 0.0001 | 0.019 |
| <i>Champsosaurus natator</i> | Aquatic (0.999) | 0.199 | | < 0.0001 | < 0.0001 | < 0.0001 |

Table S6: Taxa included in the analysis that were acquired via Morphosource, with their specimen ID, specimen institution, Morphosource media number, and ecological group used in the PCA and CVA.

| Group | Species | Specimen | Specimen Institution | Media number | Ecological Group |
|-------------------------|--------------------------------------|-------------------------|--|--------------|------------------|
| Archosauromorpha | <i>Apalone spinifera</i> | FMNH:22178 | Field Museum of Natural History | M22038 | Aquatic |
| | <i>Alca torda</i> | NMS:Z 2000.08.105 | National Museum of Scotland | M17321 | Aquatic |
| | <i>Acanthorhynchus superciliosus</i> | NHMUK:zoo:s/1966.51.209 | Natural History Museum | M17246 | Aerial |
| | <i>Alligator mississippiensis</i> | OUV:9761 | Ohio University | M39878 | Aquatic |
| | <i>Apteryx haastii</i> | NMS:Z:1913.13.748 | National Museum of Scotland | M17247 | Terrestrial |
| | <i>Corvus corax</i> | NHMUK:zoo:s/1973.66.160 | Natural History Museum | M17389 | Aerial |
| | <i>Coturnix coturnix</i> | NMS:Z.1931.43_Coturnix | National Museum of Scotland | M17723 | Terrestrial |
| | <i>Dermochelys coriacea</i> | UMZC:R:3031 | University Museum of Zoology | M22024 | Aquatic |
| | <i>Casuaris casuaris</i> | NHMUK:zoo:1939.12.9.964 | Natural History Museum | M17005 | Terrestrial |
| | <i>Gavia immer</i> | NCSM-herp-93545 | National Museum of Scotland | M17717 | Aquatic |
| | <i>Gavialis gangeticus</i> | uf:herp:118998 | Florida Museum of Natural History | M20938 | Aquatic |
| | <i>Manouria emys</i> | UMMZ:herps:227759 | University of Michigan Museum of Zoology | M38591 | Terrestrial |
| | <i>Melopsittacus undulatus</i> | NHMUK:ZOO:s/1966.51.59 | Natural History Museum | M17392 | Aerial |
| | <i>Passer domesticus</i> | NMS:Passer_unreg | National Museum of Scotland | M17720 | Aerial |
| | <i>Phalacrocorax carbo</i> | NMS:Z.2000.27.04 | National Museum of Scotland | M17423 | Aquatic |
| | <i>Phasianus colchicus</i> | NMS:Z.1931.43_Phasianus | National Museum of Scotland | M17725 | Terrestrial |
| | <i>Pyxis arachnoides</i> | UMMZ:herps:227768 | University of Michigan Museum of Zoology | M38593 | Terrestrial |
| | <i>Rhynchotus rufescens</i> | NMS:Z.1890.28.9 | National Museums of Scotland | M17408 | Terrestrial |
| | <i>Spheniscus magellanicus</i> | USNM:birds:347603 | National Museum of Natural History | M15987 | Aquatic |
| | <i>Stegoceras validum</i> | UALVP-2 | University of Alberta Laboratory for Vertebrate Paleontology | M22180 | Terrestrial |

| | | | | |
|---------------------------|------------------------|---|--------|-------------|
| <i>Sternotherus minor</i> | FMNH:211696 | Field Museum of Natural History | M22123 | Aquatic |
| <i>Struthio camelus</i> | NHMUK:ZOO:S/1927.2.5.1 | Natural History Museum | M17394 | Terrestrial |
| <i>Testudo graeca</i> | MCZ:herp:r-18161 | Museum of Comparative Zoology | M46170 | Terrestrial |
| <i>Triopticus primus</i> | TMM:31100-1030 | University of Texas Vertebrate Paleontology Collections | M7293 | Terrestrial |
| <i>Tyto alba</i> | NHMUK:ZOO:s/1981.39.1 | Natural History Museum | M17396 | Aerial |
| <i>Wannia scurriensis</i> | TTU P:00539 | University of Texas Vertebrate Paleontology Collections | M12518 | Aquatic |

| | | | | | |
|---------------------|---------------------------------|------------------------|---|--------|-------------|
| Lepidosauria | <i>Amblyrhynchus cristatus</i> | uf-herp-41558 | Florida Museum of Natural History | M20753 | Aquatic |
| | <i>Acanthosaura armata</i> | ypm:vz:ypm herr 000729 | Yale Peabody Museum | M30001 | Arboreal |
| | <i>Ahaetulla nasuta</i> | UMMZ:herps:225477 | University of Michigan Museum of Zoology | M16377 | Arboreal |
| | <i>Anolis carolinensis</i> | NCSM:herp:93545 | North Carolina Museum of Natural Sciences | M20838 | Arboreal |
| | <i>Anolis cristitellus</i> | UF:Herp:47686 | Florida Museum of Natural History | M12744 | Arboreal |
| | <i>Corallus caninus</i> | UMMZ:herps:176798 | University of Michigan Museum of Zoology | M22254 | Arboreal |
| | <i>Gekko gecko</i> | SHSVM:H:0001-2014 | Sam Houston State Vertebrate Museum | M13432 | Arboreal |
| | <i>Helicops angulatus</i> | UMMZ:herps:65852 | University of Michigan Museum of Zoology | M29152 | Aquatic |
| | <i>Pogona barbata</i> | UMM:herps:132851 | University of Michigan Museum of Zoology | M38895 | Terrestrial |
| | <i>Shinisaurus crocodilurus</i> | UF-H-60925 | Florida Museum of Natural History | M12414 | Aquatic |
| | <i>Sphenodon punctatus</i> | UF:Herp:11978 | Florida Museum of Natural History | M8675 | Terrestrial |
| | <i>Trachylepis laevis</i> | cas:herp:254838 | California Academy of Science | M15846 | Terrestrial |

Table S7: Taxa included in the analysis that were acquired via Digimorph (University of Texas High-Resolution X-ray CT Facility), with their specimen ID, specimen institution, NSF grant number, and ecological group used in the PCA and CVA.

| Group | Species | Specimen | Specimen Institution | NSF grant num. | Ecological Group |
|-------------------------|-------------------------------|-----------------|---------------------------------|----------------------------|-------------------------|
| Archosauromorpha | <i>Tomistoma schlegelli</i> * | TMM M-6342 | Texas Memorial Museum | IIS-0208675 | Aquatic |
| | <i>Rhea Americana</i> | TMM M-6721 | Texas Memorial Museum | IIS-9874781 | Terrestrial |
| Lepidosauria | <i>Lanthanotus borneensis</i> | FMNH 148589 | Field Museum of Natural History | IIS-0208675 and EF-0334961 | Aquatic |
| | <i>Varanus exanthematicus</i> | FMNH 58299 | Field Museum of Natural History | IIS-0208675 and EF-0334961 | Terrestrial |

*Additional credit to Chris Brochu

Table S8: Taxa included in this analysis that were acquired via personal contact with researchers, with their specimen ID, source, specimen institution, and ecological group used in the PCA and CVA.

| Group | Species | Specimen | Source | Specimen Institution | Ecological Group |
|------------------------------|------------------------------------|---|---|--|-----------------------|
| Choristodera | <i>Champsosaurus lindoei</i> | CMN FV 8920 | This study | Canadian Museum of Nature | ? |
| | <i>Champsosaurus natator</i> | CMN FV 8919 | This study | Canadian Museum of Nature | ? |
| Neodiapsida | <i>Youngina capensis</i> | AMNH 5561 | Nicholas Gardner | American Museum of Natural History | Terrestrial |
| Archosauromorpha | <i>Euparkeria capensis</i> | SAM-PK-7696 | Gabriela Sobral, and the Digital Collection of the Museum für Naturkunde Berlin | South African Museum | Terrestrial |
| | <i>Argillochelys antiqua</i> | NHMUK:38955 | Serjoscha Evers | Natural History Museum | Aquatic |
| | <i>Caretta caretta</i> | NHMUK:1940.3.15.1 | Serjoscha Evers | Natural History Museum | Aquatic |
| | <i>Dromaeosaurus albertensis</i> | AMNH 5356 | Lawrence Witmer | American Museum of Natural History | Terrestrial |
| | <i>Malawisaurus dixeyi</i> | Mal 202-1 | Kate Andrzejewski and Mike Polcyn | Malawi Department of Antiquities | Terrestrial |
| | <i>Massospondylus carinatus</i> | BP/1/5241 | Kimberley Chapelle | University of Witwatersrand | Terrestrial |
| | <i>Falcarius utahensis</i> | UMNH VP 15000 | Stephan Lautenschlager | Natural History Museum of Utah | Terrestrial |
| | <i>Falcarius utahensis</i> | UMNH VP 15001 | Stephan Lautenschlager | Natural History Museum of Utah | Terrestrial |
| | <i>Erlikosaurus andrewsi</i> | IGM 100/111 | Stephan Lautenschlager | Museum of Geological Institute of the Mongolian Academy of Science | Terrestrial |
| | <i>Majungasaurus crenatissimus</i> | FMNH-PR-2100 | Lawrence Witmer | Field Museum of Natural History | Terrestrial |
| | <i>Nothronychus mckinleyi</i> | AZMNH-2117 | Stephan Lautenschlager | Arizona Museum of Natural History | Terrestrial |
| | <i>Tyrannosaurus rex</i> | AMNH 5029 | Lawrence Witmer | American Museum of Natural History | Terrestrial |
| | <i>Tyrannosaurus rex</i> | AMNH 5117 | Lawrence Witmer | American Museum of Natural History | Terrestrial |
| | Lepidosauria | <i>Plioplatecarpus peckensis</i> | MOR 1062 | Hillary Maddin | Museum of the Rockies |
| <i>Iguana iguana</i> | | MCZ 2560 | Hillary Maddin | Museum of Comparative Zoology | Arboreal |
| <i>Pantherophis guttatus</i> | | Uncatalogued, available in the Maddin Lab | Fred Gaidies, and Hillary Maddin | Carleton University | Terrestrial |

*Typhlops
hypomethes*

Uncatalogued, available in
the Maddin Lab

Hillary Maddin

Carleton
University

Terrestrial

*Varanus
niloticus*

MCZ 1066

Hillary Maddin

Museum of
Comparative
Zoology

Terrestrial
