Supplementary Online Material (SOM):

A comparative analysis of the vestibular apparatus in *Epipliopithecus vindobonensis*: Phylogenetic implications

Alessandro Urciuoli [a,*], Clément Zanolli [b], Amélie Beaudet [c,d], Marta Pina [a,e], Sergio Almécija [f,g,a], Salvador Moyà-Solà [a,h,i], David M. Alba [a,*]

[a] *Institut Català de Paleontologia Miquel Crusafont, Universitat Autònoma de Barcelona, Edifici ICTA-ICP, c/ Columnes s/n, Campus de la UAB, 08193 Cerdanyola del Vallès, Barcelona, Spain*

[b] *Univ. Bordeaux, CNRS, MCC, PACEA, UMR 5199, F-33600 Pessac, France*

[c] *School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Private Bag 3, Johannesburg, WITS 2050, South Africa*

[d] *Department of Anatomy, University of Pretoria, PO Box 2034, Pretoria, 0001, South Africa*

[e] *School of Earth and Environmental Sciences, Faculty of Science and Engineering, University of Manchester, 176 Oxford Road, Manchester M13 9PL, UK*

[f] *Division of Anthropology, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA*

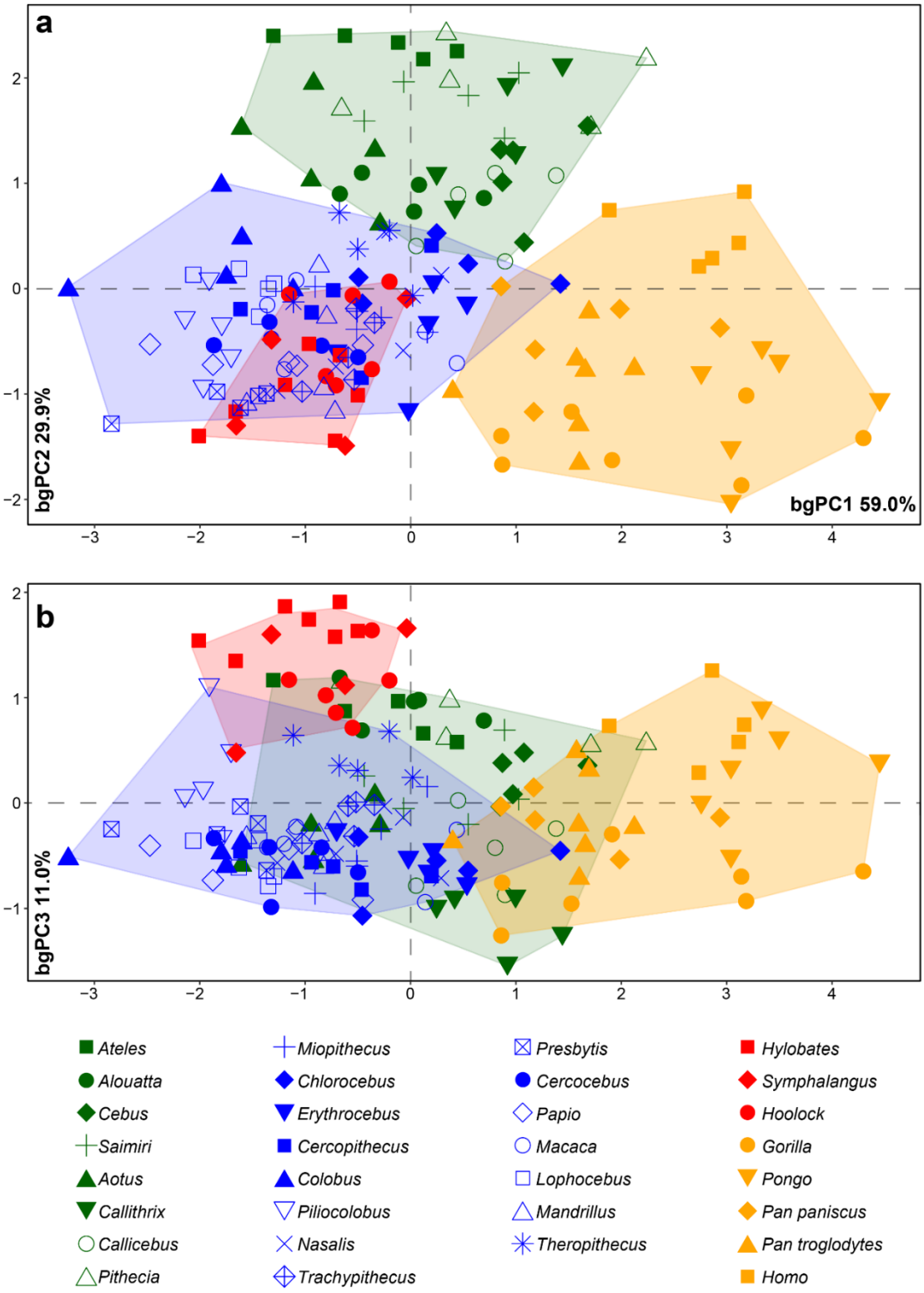
[g] *New York Consortium in Evolutionary Primatology, New York, NY, USA*

[h] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig de Lluís Companys 23, 08010 Barcelona, Spain*

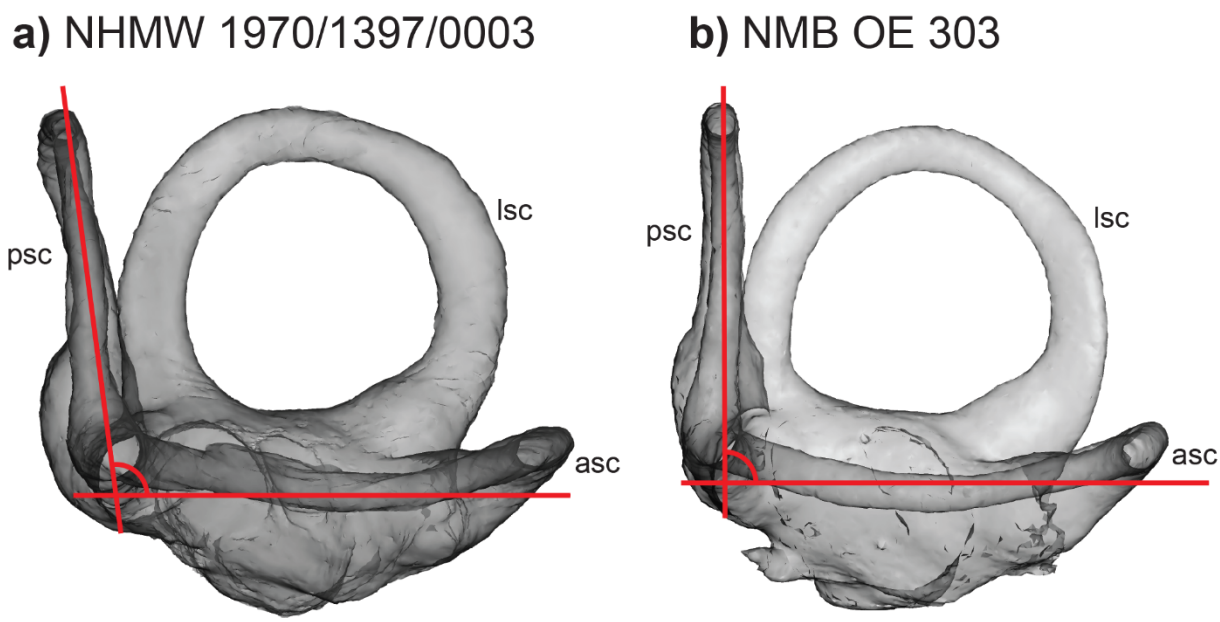
[i] *Unitat d'Antropologia (Departament de Biologia Animal, Biologia Vegetal i Ecologia), Universitat Autònoma de Barcelona, Campus de la UAB s/n, 08193 Cerdanyola del Vallès, Barcelona, Spain*

*Corresponding authors.

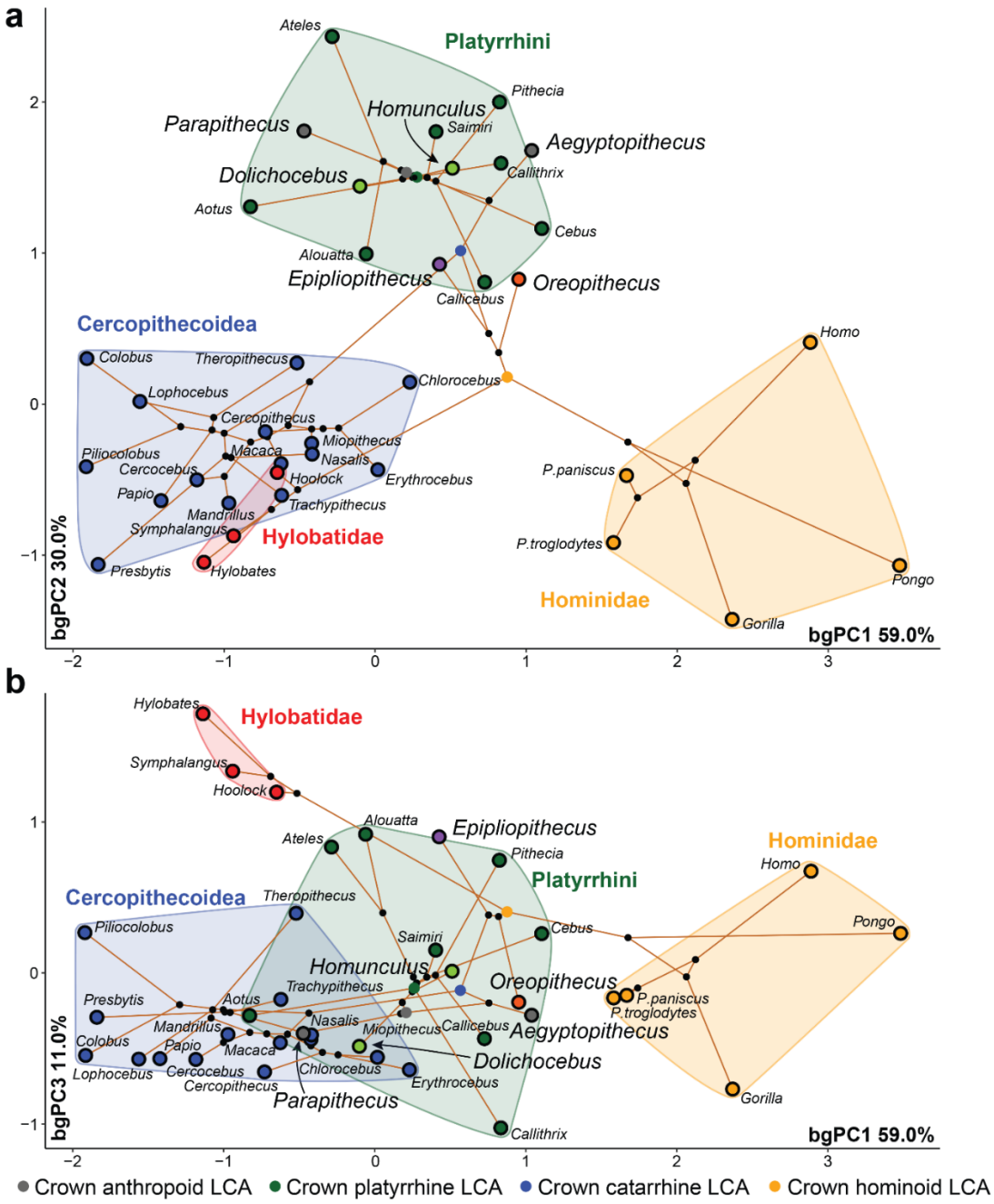
E-mail address: alessandro.urciuoli@icp.cat (A. Urciuoli); david.alba@icp.cat (D.M. Alba).



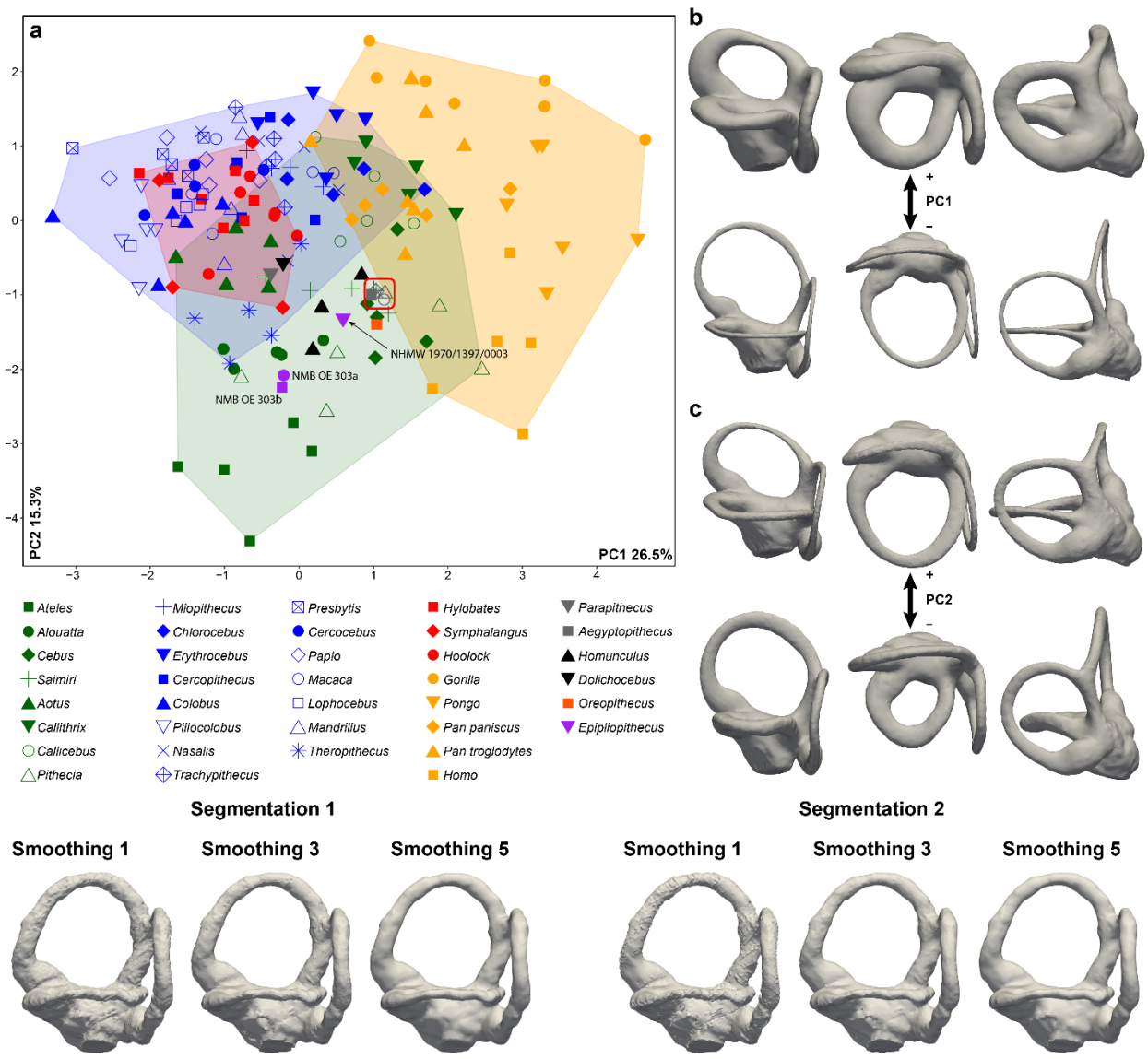
SOM Figure S1. Bivariate plots of cross-validated between-group principal component analysis (bgPCA) scores. a) bgPC2 vs. bgPC1; b) bgPC3 vs bgPC1. Variance explained by each component is given along each axis. The striking similarities (only a very slight rotation of the morphospace can be observed) between cross-validated bgPCA scores and standard ones (as shown in Fig. 6) allow us to discount spurious grouping caused by the bgPCA itself and demonstrate the presence of a grouping structure within our shape data.



SOM Figure S2. Differences in the relative orientation of the anterior and posterior canals displayed by the two *Epipliopithecus* individuals as observed from a view perpendicular to the best fit planes (represented by the red lines) of each canal. In NHMW 1970/1397/0003 (a) the planes identify an obtuse angle, while in NMB OE 303 (b) the canals form a right angle. Abbreviations: asc = anterior canal; psc = posterior canal; lsc = lateral canal.



SOM Figure S3. Reconstruction of the evolutionary history of vestibule and semicircular canal morphology in anthropoids as obtained using a phylomorphospace approach based on species centroids and considering *Epipliopithecus* as a stem hominoid (Fig. 3b): a) bgPC2 vs. bgPC1; b) bgPC3 vs. bgPC1. Variance explained by each component is given along each axis. Convex hulls depict the range of variation for a priori defined groups using the following color code: green = platyrrhines; blue = cercopithecoids; red = hylobatids; orange = hominids. The ancestral nodes discussed for assessing *Epipliopithecus* phylogenetic affinities have been marked as in Figure 1. Abbreviation: bgPCA = between-group principal component.



SOM Figure S4. Effects of manual segmentation and smoothing. Bivariate plot of the principal component analysis applied to the deformation fields of the semicircular canal and vestibule analysis. a) PC2 vs. PC1 (the variance explained by each component is given along the axis); maximum and minimum extreme conformations for PC1 (b) and PC2 (c) in lateral (left), superior (middle), and posterior (right) views. To test the effects of manual segmentation and smoothing, the *Aegyptopithecus* specimen was segmented independently by two different users. We then applied to the two resulting models three different degrees of smoothing (kernel 1, 3 and 5), and included the six resulting models in our PCA analysis to check the distance between the different versions of the same specimen. The visual inspection of the scatter of points, together with the observed relative error (3.8%), discounts a significant effect of the segmentation on the results of our analyses.

SOM Table S1

Sample sizes of the extant species included in the comparative sample.

Species	*n*	M	F	?
Alouatta palliata	5	3	2	0
Aotus trivirgatus	5	1	4	0
Ateles geoffroyi	5	1	4	0
Callicebus moloch	5	5	0	0
Callithrix argentata	5	4	1	0
Cebus apella	5	3	2	0
Cercocebus galeritus	5	0	5	0
Cercopithecus mitis	5	2	3	0
Chlorocebus pygerythrus	5	2	3	0
Colobus guereza	5	3	2	0
Erythrocebus patas	5	3	2	0
Gorilla gorilla	7	2	5	0
Homo sapiens	5	2	3	0
Hoolock hoolock	6	2	4	0
Hylobates lar	7	0	7	0
Lophocebus albigena	5	2	3	0
Macaca fascicularis	5	1	4	0
Mandrillus sphinx	5	5	0	0
Miopithecus talapoin	5	3	2	0
Nasalis larvatus	5	0	5	0
Pan paniscus	5	1	4	0
Pan troglodytes	7	4	3	0
Papio Anubis	5	3	2	0
Piliocolobus badius	5	4	1	0
Pithecia monachus	5	1	1	3
Pongo pygmaeus	6	0	4	2
Presbytis rubicunda	5	2	3	0
Saimiri sciureus	5	3	2	0
Symphalangus syndactylus	4	2	2	0
Theropithecus gelada	5	4	1	0
Trachypithecus cristatus	5	0	5	0

Abbreviations: M = male; F = female; ? = unknown sex.

SOM Table S2

List of µCT image stacks of the fossil comparative sample.

Catalog No.	Taxon	MorphoSource ID[a]	Voxel size (mm)[b]
CGM 85785	*Aegyptopithecus zeuxis*	M2377	0.05600 × 0.05600 × 0.06379
MPM-PV 30501	*Homunculus patagonicus*	M7940	0.040
MPM-PV 30502	*Homunculus patagonicus*	M7941	0.039
MPM-PV 30503	*Homunculus patagonicus*	M7942	0.044
MACN 14128	*Dolichocebus gaimanensis*	M7978	0.047
BAC 208	*Oreopithecus bambolii*[c]	—	0.02905
DPC 18651	*Parapithecus grangeri*	M90	0.0353

Abbreviations: BAC = Baccinello (field acronym; housed at Naturhistorisches Museum Basel, Switzerland); CGM = Egyptian Geological Museum, Cairo, Egypt; MPM-PV = Museo Regional Provincial Padre M.J. Molina, Río Gallegos, Argentina; MACN = Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina; DPC = Duke Lemur Center, Durham, NC, USA.

[a] All the stacks available from MorphoSource can be accessed by searching their ID number ('M' excluded) at https://www.morphosource.org.

[b] Voxel size for isometric µCT image stacks repeated just once.

[c] The µCT scan was kindly provided by Lorenzo Rook.

SOM Table S3

Source data for Figure 5 consisting of log-transformed canal length (ln L, in mm) and log-transformed cube root of canal volume (ln VolSC, in mm) for extant species.

ID	Species	ln L	ln VolSC
DU LP 02	*Alouatta palliata*	3.654	0.929
DU LP 04	*Alouatta palliata*	3.529	0.699
DU LP 06	*Alouatta palliata*	3.658	0.920
DU LP 10	*Alouatta palliata*	3.551	0.909
DU LP 12	*Alouatta palliata*	3.660	0.867
MCZ 19801	*Aotus trivirgatus*	3.220	0.614
MCZ 19802	*Aotus trivirgatus*	3.322	0.590
MCZ 19805	*Aotus trivirgatus*	3.279	0.648
MCZ 27214	*Aotus trivirgatus*	3.314	0.651
MCZ 30562	*Aotus trivirgatus*	3.213	0.627
MCZ 10138	*Ateles geoffroyi*	3.685	1.033
MCZ 29626	*Ateles geoffroyi*	3.596	0.886
MCZ 29628	*Ateles geoffroyi*	3.620	0.985
MCZ 29658	*Ateles geoffroyi*	3.559	0.953
MCZ BOM 5351	*Ateles geoffroyi*	3.774	1.003
MCZ 20186	*Callicebus moloch*	3.096	0.634
MCZ 20188	*Callicebus moloch*	3.109	0.713
MCZ 26922	*Callicebus moloch*	3.098	0.688
MCZ 30559	*Callicebus moloch*	3.109	0.632
MCZ 30564	*Callicebus moloch*	3.116	0.776
MCZ 30579	*Callithrix argentata*	3.294	0.757
MCZ 30580	*Callithrix argentata*	3.301	0.787
MCZ 30582	*Callithrix argentata*	3.291	0.760
MCZ 30583	*Callithrix argentata*	3.394	0.787
MCZ 32164	*Callithrix argentata*	3.277	0.838
MCZ 27891	*Cebus apella*	3.407	0.873
MCZ 31063	*Cebus apella*	3.455	0.872
MCZ 37833	*Cebus apella*	3.522	0.908
MCZ 41090	*Cebus apella*	3.507	0.907
MCZ 49635	*Cebus apella*	3.526	0.901
AMNH-M 52634	*Cercocebus galeritus*	3.661	0.891
AMNH-M 52635	*Cercocebus galeritus*	3.737	0.845
AMNH-M 52640	*Cercocebus galeritus*	3.708	0.791
AMNH-M 52641	*Cercocebus galeritus*	3.691	0.860
AMNH-M 52645	*Cercocebus galeritus*	3.553	0.855
MCZ 22734	*Cercopithecus mitis*	3.447	0.758
MCZ 25022	*Cercopithecus mitis*	3.349	0.773

MCZ 26832	*Cercopithecus mitis*	3.521	0.798
MCZ 39389	*Cercopithecus mitis*	3.485	0.752
MCZ 44264	*Cercopithecus mitis*	3.555	0.712
SIU 4792	*Chlorocebus pygerythrus*	3.393	0.889
SIU 4793	*Chlorocebus pygerythrus*	3.529	0.941
SIU 4794	*Chlorocebus pygerythrus*	3.642	0.948
SIU 4795	*Chlorocebus pygerythrus*	3.484	0.905
SIU 4796	*Chlorocebus pygerythrus*	3.611	0.935
AMNH-M 52211	*Colobus guereza*	3.737	0.894
AMNH-M 52213	*Colobus guereza*	3.720	0.913
AMNH-M 52225	*Colobus guereza*	3.649	0.893
AMNH-M 52237	*Colobus guereza*	3.743	0.890
AMNH-M 52249	*Colobus guereza*	3.819	0.806
MCZ 37280	*Erythrocebus patas*	3.615	0.941
MCZ 47015	*Erythrocebus patas*	3.626	1.056
MCZ 47016	*Erythrocebus patas*	3.659	1.065
MCZ 47017	*Erythrocebus patas*	3.566	0.928
MCZ 47018	*Erythrocebus patas*	3.567	0.902
AMNH-A 999686	*Gorilla gorilla*	3.807	1.261
AMNH-A 999687	*Gorilla gorilla*	3.755	1.297
AMNH-M 167338	*Gorilla gorilla*	3.905	1.351
AMNH-M 54356	*Gorilla gorilla*	3.700	1.387
MCZ 17684	*Gorilla gorilla*	3.866	1.223
MCZ 26850	*Gorilla gorilla*	3.749	1.312
MCZ 37264	*Gorilla gorilla*	3.726	1.108
EMBR 121	*Homo sapiens*	3.834	1.282
EMBR 179	*Homo sapiens*	3.853	1.294
EMBR 212	*Homo sapiens*	3.690	1.204
EMBR 215	*Homo sapiens*	3.733	1.347
EMBR 281	*Homo sapiens*	3.857	1.402
AMNH-M 112673	*Hoolock hoolock*	3.733	0.981
AMNH-M 112720	*Hoolock hoolock*	3.728	0.951
AMNH-M 112983	*Hoolock hoolock*	3.689	1.037
AMNH-M 201742	*Hoolock hoolock*	3.765	1.071
AMNH-M 83421	*Hoolock hoolock*	3.752	1.025
AMNH-M 83425	*Hoolock hoolock*	3.747	0.941
MCZ 41411	*Hylobates lar*	3.587	0.812
MCZ 41412	*Hylobates lar*	3.677	0.886
MCZ 41416	*Hylobates lar*	3.725	0.815
MCZ 41418	*Hylobates lar*	3.734	0.828
MCZ 41421	*Hylobates lar*	3.650	0.858

MCZ 41424	*Hylobates lar*	3.656	0.882
MCZ 41452	*Hylobates lar*	3.615	0.829
AMNH-M 52596	*Lophocebus albigena*	3.686	0.881
AMNH-M 52603	*Lophocebus albigena*	3.753	0.933
AMNH-M 52606	*Lophocebus albigena*	3.582	0.773
AMNH-M 52607	*Lophocebus albigena*	3.724	0.834
AMNH-M 52615	*Lophocebus albigena*	3.712	0.880
MCZ 12758	*Macaca fascicularis*	3.541	0.855
MCZ 22277	*Macaca fascicularis*	3.618	0.752
MCZ 23812	*Macaca fascicularis*	3.478	0.803
MCZ 23813	*Macaca fascicularis*	3.574	0.724
MCZ 35765	*Macaca fascicularis*	3.566	0.754
AMNH-A 9912049	*Mandrillus sphinx*	3.677	0.923
AMNH-A 9912056	*Mandrillus sphinx*	3.693	0.922
AMNH-M 89362	*Mandrillus sphinx*	3.669	0.915
AMNH-M 89364	*Mandrillus sphinx*	3.719	0.870
AMNH-M 89365	*Mandrillus sphinx*	3.614	0.856
MCZ 19976	*Miopithecus talapoin*	3.385	0.742
MCZ 23196	*Miopithecus talapoin*	3.466	0.791
MCZ 23197	*Miopithecus talapoin*	3.346	0.671
MCZ 34264	*Miopithecus talapoin*	3.369	0.689
MCZ 37278	*Miopithecus talapoin*	3.462	0.748
MCZ 37342	*Nasalis larvatus*	3.692	0.949
MCZ 41555	*Nasalis larvatus*	3.670	0.834
MCZ 41559	*Nasalis larvatus*	3.670	0.974
MCZ 41560	*Nasalis larvatus*	3.689	0.994
MCZ 41562	*Nasalis larvatus*	3.712	1.067
AMNH-M 86857	*Pan paniscus*	3.691	1.120
IPS9033	*Pan paniscus*	3.680	1.079
MCZ 38018	*Pan paniscus*	3.691	1.086
MCZ 38019	*Pan paniscus*	3.579	1.092
MCZ 38020	*Pan paniscus*	3.650	1.170
AMNH-M 167342	*Pan troglodytes*	3.672	1.193
AMNH-M 167344	*Pan troglodytes*	3.702	1.155
AMNH-M 51204	*Pan troglodytes*	3.737	1.212
IPS5698	*Pan troglodytes*	3.766	1.227
MCZ 17702	*Pan troglodytes*	3.667	1.051
MCZ 23167	*Pan troglodytes*	3.588	1.025
MCZ 26847	*Pan troglodytes*	3.636	1.082
AMNH-M 52677	*Papio anubis*	3.815	0.948
MCZ 17342	*Papio anubis*	3.643	0.855

MCZ 26473	*Papio anubis*	3.677	0.863
MCZ 31619	*Papio anubis*	3.855	0.896
MCZ BOM 8466	*Papio anubis*	3.594	0.872
MCZ 24080	*Piliocolobus badius*	3.496	0.649
MCZ 24775	*Piliocolobus badius*	3.598	0.609
MCZ 24793	*Piliocolobus badius*	3.588	0.685
MCZ 25627	*Piliocolobus badius*	3.512	0.624
MCZ 25631	*Piliocolobus badius*	3.604	0.694
MCZ 20265	*Pithecia monachus*	3.431	0.766
MCZ 20266	*Pithecia monachus*	3.321	0.909
MCZ 27124	*Pithecia monachus*	3.473	0.950
MCZ 30720	*Pithecia monachus*	3.315	0.995
MCZ BOM 5057	*Pithecia monachus*	3.471	0.943
IPS10647	*Pongo pygmaeus*	3.660	1.363
IPS10651	*Pongo pygmaeus*	3.750	1.342
IPS9031	*Pongo pygmaeus*	3.500	1.205
IPSSN	*Pongo pygmaeus*	3.662	1.231
MHNTZOO 201108	*Pongo pygmaeus*	3.626	1.270
SENCK 1576UU	*Pongo pygmaeus*	3.712	1.298
MCZ 35712	*Presbytis rubicunda*	3.678	0.877
MCZ 37370	*Presbytis rubicunda*	3.579	0.837
MCZ 37371	*Presbytis rubicunda*	3.619	0.775
MCZ 37372	*Presbytis rubicunda*	3.516	0.651
MCZ 37772	*Presbytis rubicunda*	3.616	0.841
AMNH-M 33875	*Saimiri sciureus*	3.350	0.788
AMNH-M 72068	*Saimiri sciureus*	3.284	0.832
AMNH-M 72074	*Saimiri sciureus*	3.280	0.785
AMNH-M 72078	*Saimiri sciureus*	3.411	0.775
AMNH-M 72079	*Saimiri sciureus*	3.270	0.766
AMNH-M 102724	*Symphalangus syndactylus*	3.671	0.964
AMNH-M 106583	*Symphalangus syndactylus*	3.739	0.952
MCZ 36031	*Symphalangus syndactylus*	3.732	0.881
MCZ 36032	*Symphalangus syndactylus*	3.793	0.849
AMNH-M 19549	*Theropithecus gelada*	3.667	0.946
AMNH-M 238034	*Theropithecus gelada*	3.606	0.740
AMNH-M 60568	*Theropithecus gelada*	3.627	0.890
AMNH-M 80126	*Theropithecus gelada*	3.661	0.807
AMNH-M 90309	*Theropithecus gelada*	3.630	0.871
MCZ 35567	*Trachypithecus cristatus*	3.599	0.888
MCZ 35584	*Trachypithecus cristatus*	3.639	0.940
MCZ 35586	*Trachypithecus cristatus*	3.653	0.937

MCZ 35597	*Trachypithecus cristatus*	3.651	0.889
MCZ 35603	*Trachypithecus cristatus*	3.664	0.947

Abbreviations: ID = catalog number; ln L = log-transformed canal length; ln VolSC = log-transformed cube root of canal volume; DU EA LP = Duke University, Evolutionary Anthropology, Durham, NC, USA; MCZ = Museum of Comparative Zoology, Harvard University, Cambridge, MA, USA; MCZ BOM = Museum of Comparative Zoology ("Bone of Mammals"), Harvard University, Cambridge, MA, USA; AMNH-M = American Museum of Natural History (Mammalogy collection), New York, NY, USA; AMNH-A = American Museum of Natural History (Anthropology collection), New York, NY, USA; SENCK = Senckenberg Naturmuseum, Frankfurt, Germany; MHNTZOO = Muséum d'histoire naturelle de Toulouse (Zoologie), Toulouse, France; IPS = collections of the ICP, Sabadell, Spain; SIU = Southern Illinois University, Carbondale, IL, USA.

SOM Table S4

Matrix of character states coded for the extant and fossil species included in the analysis.[a]

Species	#1	#2	#3	#4	#5	#6	#7
Aegyptopithecus zeuxis	0	0	2	0	2	0	0
Alouatta palliata	0	0	B	0	2	0	0
Aotus trivirgatus	0	0	2	0	2	0	A
Ateles geoffroyi	0	0	2	0	2	0	0
Callicebus moloch	0	0	2	0	2	0	0
Callithrix argentata	0	0	2	0	2	0	0
Cebus apella	0	0	B	0	2	0	0
Cercocebus galeritus	0	0	1	0	1	0	1
Cercopithecus mitis	0	0	1	0	B	0	1
Chlorocebus pygerythrus	0	0	1	0	1	0	1
Colobus guereza	0	0	1	0	1	0	1
Dolichocebus gaimanensis	0	0	2	0	2	0	0
Epipliopithecus vindobonensis	0	0	1	0	2	0	0
Erythrocebus patas	0	0	1	0	1	0	1
Gorilla gorilla	1	1	0	0	A	1	B
Homo sapiens	1	1	1	0	0	0	2
Homunculus patagonicus	0	0	2	0	B	0	0
Hoolock hoolock	0	0	A	1	1	1	2
Hylobates lar	0	0	0	1	1	1	2
Lophocebus albigena	0	0	1	0	B	0	1
Macaca fascicularis	0	0	1	0	1	0	1
Mandrillus sphinx	0	0	1	0	1	0	1
Miopithecus talapoin	0	0	1	0	1	0	A
Nasalis larvatus	0	0	1	0	A	0	2
Oreopithecus bambolii	1	1	0	1	1	0	2
Pan paniscus	1	1	0	0	2	1	1
Pan troglodytes	1	1	0	0	B	1	B
Papio anubis	0	0	1	0	1	0	1
Parapithecus grangeri	0	0	2	0	2	0	0
Piliocolobus badius	0	0	1	0	1	0	B
Pithecia monachus	0	0	1	0	2	0	A
Pongo ssp	1	1	0	1	A	1	2
Presbytis rubicunda	0	0	1	0	1	0	2
Saimiri sciureus	0	0	2	0	2	0	0
Symphalangus syndactylus	0	0	A	1	A	A	2

Theropithecus gelada	0	0	1	0	0	0	1
Trachypithecus cristatus	0	0	1	0	A	0	1

[a]Abbreviations for variable characters: A = (0,1); B = (0,2). See Table 7 for character definitions and Table 8 for coding of extinct taxa and the last common ancestors of main anthropoid clades.