

Humans and great apes share a large frontal cortex

K. Semendeferi¹, A. Lu¹, N. Schenker¹ and H. Damasio²

¹Department of Anthropology, University of California at San Diego, La Jolla, California 92093

²Department of Neurology, University of Iowa, Iowa City, Iowa 52242

Correspondence should be addressed to K.S. (ksemende@ucsd.edu)

Published online: 19 February 2002, DOI: 10.1038/nn814

Some of the outstanding cognitive capabilities of humans are commonly attributed to a disproportionate enlargement of the human frontal lobe during evolution. This claim is based primarily on comparisons between the brains of humans and of other primates, to the exclusion of most great apes. We compared the relative size of the frontal cortices in living specimens of several primate species, including all extant hominoids, using magnetic resonance imaging. Human frontal cortices were not disproportionately large in comparison to those of the great apes. We suggest that the special cognitive abilities attributed to a frontal advantage may be due to differences in individual cortical areas and to a richer interconnectivity, none of which required an increase in the overall relative size of the frontal lobe during hominid evolution.

Solid evidence exists today about the complexity of the organization of the primate frontal cortex^{1,2}, but how this organization has evolved remains largely unexplored, as has been noted repeatedly^{3–5}. Few studies have addressed the organization of this part of the brain from a comparative perspective, and thus most evolutionary reconstructions still rely on the notion of a disproportionately enlarged frontal cortex in humans. It is this disproportionate enlargement that is considered to be largely responsible for the uniqueness of human cognitive specialization⁶.

The evidence in favor of the traditional notion that the frontal cortex has enlarged disproportionately in human evolution comes primarily from two sources^{7,8}. An important problem with those earlier sources, as well as more recent studies^{9–11}, is that they are based on the analysis of one or two hemispheres of a few primates and other nonprimate mammals, usually to the exclusion of apes, our closest relatives. As a further complication, the nomenclature used in this literature is inconsistent³. On occasion the term 'frontal' is used to refer to the entire sector of the hemisphere in front of the central sulcus (the frontal lobe); on other occasions it is used to refer only to the cortex of the frontal lobe or, even more restrictively, to the prefrontal cortex alone.

The final and incontrovertible analysis of the subsectors of the frontal lobe in terms of comparative neuroanatomy will come only from detailed cytoarchitectonic studies. The prohibitive cost of such studies and the scarcity of the great ape material, however, make it unlikely that these will be done in the foreseeable future. In the meantime, structural magnetic resonance imaging offers the possibility of conducting a cross-species, multiple-subject study of this problem. Though it is by no means definitive, we regard this approach as capable of yielding a provisional assessment of the problem. In a set of earlier studies, we have shown that the values for the relative size of the frontal lobe as a whole overlap in great apes and humans^{12,13}. Nevertheless, those studies leave open the possibility that the overlap might

be due to a disproportionate enlargement of subcortical structures in the apes (such as the basal ganglia that largely underlie frontal cortices), which could obscure differences in the size of the cortex of the frontal lobe. In the hope of assessing this possibility, we undertook a new and comprehensive comparative study of the cortical mantle in humans and apes. We used magnetic resonance scans of the brains of living subjects: humans, apes of all extant species and selected monkeys. Our sample was thus larger than any used in previous comparative neuroanatomical studies. We examined the overall volume of the frontal cortex, and of two of its subdivisions that are reliably identifiable on the basis of gross anatomical markers in humans and apes: the cortex of the precentral gyrus, and the remaining frontal cortex on the dorsal, mesial and orbital surfaces of the frontal lobe (Fig. 1). We found that some primates (lesser apes and monkeys) had a relatively smaller frontal cortex than humans, but great apes did not.

RESULTS

As expected, humans had the largest frontal cortex. Individual values in humans ranged from 238.8 cm³ to 329.8 cm³ and in the great apes from 50.4 cm³ (in a chimpanzee) to 111.6 cm³ (in an orangutan). For the lesser apes (gibbons) the values varied between 13.2 cm³ and 16 cm³, and for the monkeys (rhesus, cebus) they varied between 13.3 cm³ and 15.1 cm³. Humans also had the largest values for the cortex of the precentral gyrus (43.3–53.8 cm³), followed by the great apes (ranging from 11.2 cm³ in one chimpanzee to 28.4 cm³ in one orangutan) and then the gibbons (2.6–3.9 cm³). (As noted in Methods, the separation of the cortex belonging to the precentral gyrus and to the rest of the frontal lobe was not performed for monkeys.) The rest of the frontal cortex rostral to the precentral gyrus had a similar distribution. Humans ranged from 206.8 cm³ to 283.4 cm³, great apes from 39.1 cm³ (in one chimpanzee) to 76.7 cm³ (in one orangutan) and gibbons from 10.6 cm³ to 12.2 cm³.



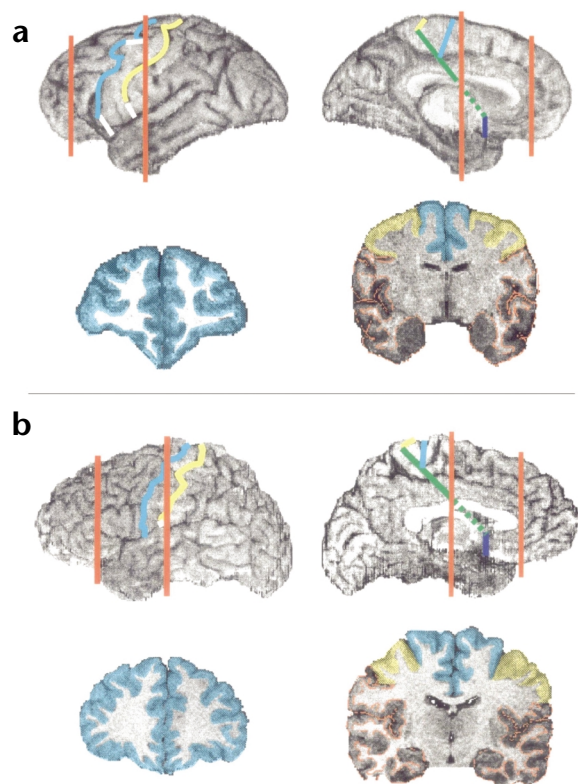


Fig. 1. Three-dimensional reconstruction of the brain of (a) a common chimpanzee and (b) a human. The lateral and mesial surfaces of the left hemisphere are shown (not to scale). The central and precentral sulci are marked in yellow and cyan, respectively. The posterior end of the frontal cortex is marked by the yellow line (central sulcus). The white segments correspond to connections drawn between discontinuous segments of these sulci. On the mesial surface, the posterior end of the frontal cortex is marked by the solid green line and the blue line marks the end of the orbitofrontal cortex. The red lines mark the position of the coronal sections through the hemisphere shown below. On the coronal sections, cyan indicates frontal cortices anterior to the precentral sulcus, yellow indicates the cortex of the precentral gyrus and red the rest of the cortex of the hemisphere.

individual great apes showed values that overlapped with those of humans. Specifically, two chimpanzees, one bonobo and one gorilla were within the lower end of the human range. There was extensive overlap among the great apes themselves, but not between gibbons and the rest of the hominoids. In neither subsector of the frontal cortex did humans have values larger than expected for an ape of their brain size.

DISCUSSION

Although the absolute differences in size of the frontal cortex between humans and other primates were large, the frontal cortex in humans and great apes occupied a similar proportion of the cortex of the cerebral hemispheres. The range of relative values did overlap in the different hominoid species. The smaller primates (gibbons and monkeys) had a smaller percentage of their total cortex occupied by frontal cortices, and the range of their values did not overlap with that of the larger hominoids. In relation to overall brain size, the human frontal cortex was as large as expected for a primate brain of human size.

As noted, with respect to the subsectors of the frontal lobe, any definitive statements can only come from comparative cytoarchitectonic studies of the brains of extant ape species and humans, which would be so costly as to preclude their being carried out anytime soon. Therefore, our finding that the two subsectors of the frontal cortex (cortex of the precentral gyrus and cortex rostral to the precentral sulcus) are not disproportionately larger in humans, though provisional, should prove useful until more definitive data become available.

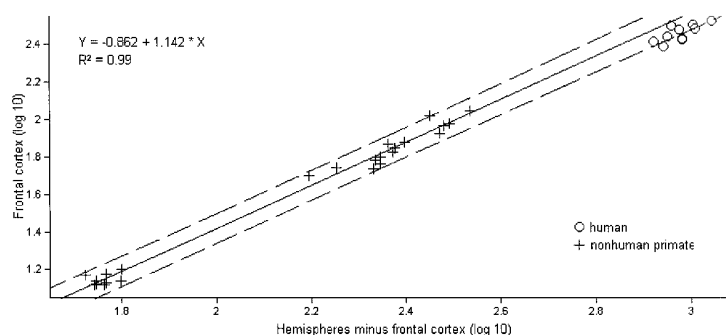
How can we account for the discrepancy between earlier findings (Table 1) and ours? Sample size is the most likely factor. Previous studies have had sample sizes of only one or two hemispheres per species and only one or two of the ape species have been included^{7,8}. Brodmann⁷ reports a 6% increase in the 'total frontal lobe surface' of the human brain compared to the chimpanzee brain. In our sample, we could find a comparable difference, but only when selected humans and chimpanzees were

Nevertheless, the human frontal cortex was not larger than expected for a primate brain of human size (Fig. 2). When the volume of the frontal cortex was regressed against the volume of the entire hemisphere and a best-fit line was drawn through all nonhuman primates, the observed human values did not fall above the prediction interval.

In addition, calculating the frontal cortex volume as a percentage of the cortex volume of the hemispheres gave values for humans on a par with those for the great apes (Fig. 3). The range of individual values for the frontal cortex of humans, which varied between 36.4% and 39.3%, overlapped with those of the orangutans (36.6–38.7%), chimpanzees (32.4–37.5%) and gorillas (35% and 36.9%). Values for gibbons (27.5–31.4%) and monkeys (29.4–32.3%) fell outside the range of great apes and humans, and their mean relative values were significantly smaller (standard two-sample Student's *t*-test) than those of the great apes ($t = 8.5444$, d.f. = 22, $p \leq 0.001$) and humans ($t = 13.8717$, d.f. = 17, $p \leq 0.0001$).

In relation to the cortex of the precentral gyrus as a percent of hemispheric cortex the two orangutans stood out, with the largest relative values (10.2% and 10.4%); the remaining individual values across hominoid species overlapped from 9% in one chimpanzee to 5.5% in one gibbon. Humans fell within this hominoid range (5.4–7.9%). The relative size of the remaining frontal cortex ranged from 28.8% to 33% in humans, 25.5% to 29.7% in the great apes and 22.0% to 23.8% in the gibbons. A few

Fig. 2. Logarithmic plot of the volume of the frontal cortex against the total volume of the hemispheres minus the frontal cortex. A best-fit regression line is drawn through all nonhuman primate subjects. Dotted lines represent the prediction interval. The human observed values are added on the plot.



Volume of frontal cortex

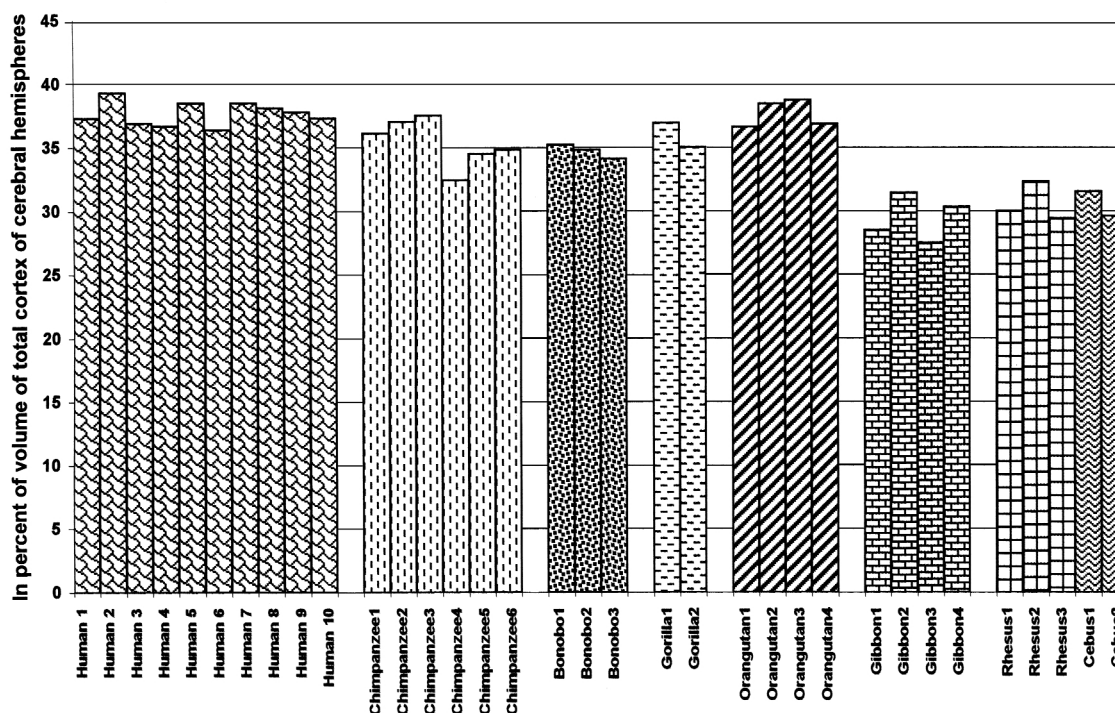


Fig. 3. Individual values of the relative volume of the frontal cortex as a percent of the volume of the total hemispheric cortex.

compared (for example, human 2 versus chimpanzee 4 in Fig. 3). Removal of some of the 'high-end' great ape subjects or of the 'lower-end' human subjects in our study would have yielded results similar to those reported earlier. The inclusion of only selected primate species and an underrepresentation of the great apes are other possible reasons for the discrepant results. Even using our larger sample, if the comparison had been restricted to humans and smaller primates (Fig. 3) and had excluded most of the great apes, the results would have been more consonant with the older results, because gibbons and monkeys do, in fact, have a relatively smaller frontal cortex than humans. In addition, we calculated volumes of the cortical regions of interest, while earlier studies^{7,8} rely on surface estimates. We doubt that this could account for most of the variance, however, given that the cortical volume is highly correlated with the surface of the cortical sheet. Finally, earlier studies use postmortem specimens as opposed to the living subjects included here, which leaves open the possibility that differential shrinkage could have affected the results.

An issue that needs further investigation is the size of the prefrontal cortex proper (after exclusion of motor, premotor and limbic cortices). We do not think that this can be addressed by gross anatomical studies. No sulcal landmarks can be used reliably to establish the transition of prefrontal cortex to premotor cortex or the borders of individual cortical areas, and thus this issue can only be resolved on the basis of quantitative cytoarchitectonic studies. Recent reports of such studies suggest that the size and organization of individual cortical areas in the hominoid prefrontal cortex may set humans apart from the great apes. Specifically, in terms of size, Brodmann's

area 10 is reported to be relatively larger in the human brain¹⁴ when compared to the ape brain, while Brodmann's area 13 is smaller¹⁵. In the present study, we excluded the cortex of the precentral gyrus from the total frontal cortex in order to examine a subsector of the frontal cortex that includes all of the prefrontal cortices. Brodmann's area 6 and some limbic frontal cortices on the mesial surface were also included, however. We found that this region is as large as expected for an ape brain of human size, and that the relative values among individual humans and individual great apes (but not lesser apes or monkeys) overlapped. This result goes against the large relative differences in the prefrontal cortex between humans and great apes reported in previous publications (Brodmann⁷, who reports as much as a 12% enlargement in relation to the chimpanzee, and Deacon⁶, who sets it at 202% more than expected for a brain of the human size), even presuming the possibility of a much smaller premotor and limbic sector.

Table 1. The relative size of the frontal cortex.

	Brodmann (1909) ^{7*}	Blinkov & Glezer (1965) ^{8*}	Present study ^{**}
Human	36.3	32.8	37.7 (± 0.9)
Chimpanzee	30.5	22.1	35.4 (± 1.9)
Bonobo	NA	NA	34.7 (± 0.6)
Gorilla	NA	NA	35.0 and 36.9
Orangutan	NA	21.3	37.6 (± 1.1)
Gibbon	21.4	21.2	29.4 (± 1.8)
Macaque	NA	NA	30.6 (± 1.5)
Cebus	22.5	NA	29.6 and 31.5

*Surface of frontal cortex in % of surface of cortex of cerebral hemispheres. **Volume of frontal cortex in % of volume of cortex of cerebral hemispheres. NA, not available.



The fact that the relative size of the frontal cortex is similar in humans and great apes does not mean that the frontal cortices are less significant to hominid cognitive specialization than has been suggested^{1,3,16}. The frontal cortices could support the outstanding cognitive capabilities of humans without undergoing a disproportionate overall increase in size. This region may have undergone a reorganization that includes enlargement of selected, but not all, cortical areas to the detriment of others. The same neural circuits might be more richly interconnected within the frontal sectors themselves and between those sectors and other brain regions. Also, subsectors of the frontal lobe might have undergone a modification of local circuitry, expressed, for instance, in the form of distinct cytoarchitectonic patterns. In addition, microscopic or macroscopic subsectors might have been added to the mix or dropped.

There is already some evidence bearing on these possibilities. Findings from the comparative histological studies of the frontal cortex discussed above^{14–15} and from other brain regions^{17–18} suggest that the internal organization and size of individual cortical areas are specialized among the hominoids. In a previous study, we found that the relative volume of white matter underlying prefrontal association cortices is larger in humans than in great apes (Semendeferi, K., Damasio, H. & Van Hoesen, G.W., *Soc. Neurosci. Abstr.*, 20, 587.7, 1994). This is compatible with the idea that neural connectivity has increased in the human brain¹⁹. More recently we have shown that orangutans have a smaller orbitofrontal sector than other apes or humans (Semendeferi, K., Lu, A., Desgouttes, A.M. & Damasio, H., *Am. J. Phys. Anthr., Suppl.* 30, 278, 2000), which suggests that some differences can be found in small subsectors of the frontal lobe at a gross level. Thus, it seems possible, and even likely, that either subsectors of the frontal lobes or individual frontal cortical areas have become specialized during hominoid and hominid evolution. Cognitive specialization in each hominoid species would be related to mosaic evolution²⁰ and reorganization of specific areas in this and other parts of the brain.

In conclusion, it appears that the traditional notion that disproportionately large frontal lobes and frontal cortices are the hallmark of hominid brain evolution is not supported. Homogeneity in the scaling relations of some of the major sectors in the primate brain has been suggested before^{21–22}, and our results showed that such homogeneity also exists with respect to the size of the frontal cortex. Our data also point to the possibility that the inclusion of closely related species and larger numbers of individuals per species may reveal that certain areas of the brain present slight modifications expressed even at the gross level²⁰. The findings on gibbons, macaques and cebus monkeys reported here, and results from another study involving humans and baboons¹¹, point to a possible great ape/human specialization in regard to an enlarged frontal cortex that may set larger hominoids apart from other anthropoid primates. The enlargement of the frontal cortex in great apes and humans parallels the emergence in this same group of a unique morphological type of neurons in the anterior cingulate cortex, which has extensive connections with the prefrontal cortex²³. Relatively large frontal lobes and frontal cortices would be shared hominoid features that would have appeared prior to the Plio-Pleistocene along with certain reorganizational features reported to be present in the precursors of hominoids²⁴.

METHODS

We obtained scans of the brains of 24 nonhuman primate subjects (from the Yerkes Regional Primate Research Center, Emory University, Atlanta, Georgia) and of ten normal human subjects (from the Department of Neurology, University of Iowa, Iowa City). Nonhuman primate experi-

mental use was approved by the Emory University IACUC (protocol number 062-95Y) and human subjects provided informed consent in accord with the policies of IRB of the University of Iowa College of Medicine. The subjects included adult individuals of both sexes. The nonhuman primates included 15 great apes (6 chimpanzees, 3 bonobos, 2 gorillas, 4 orangutans), 4 lesser apes (gibbons) and 5 monkeys (3 rhesus and 2 cebus). One chimpanzee (chimpanzee 1), one bonobo (bonobo 1) and the four gibbons were wild caught; the other nonhuman primates were born in captivity. Thin-cut magnetic resonance images were obtained for all human subjects in a General Electric 4096 Plus scanner operating at 1.5 Tesla, using the following protocol: SPGR/50, TR 24, TE 5, NEX 2, FOV 24 cm, matrix 256 × 192, 124 contiguous coronal slices, 1.6 mm thick. The nonhuman primates were scanned in a Phillips Gyroscan NT, and thickness of axial slices varied between 1.2 and 1.4 mm with a slice overlap of 0.6 mm (FOV 124–230 cm).

All brains were reconstructed in three dimensions using Brainvox^{25,26}, an interactive family of programs designed to reconstruct, segment and measure brains from magnetic resonance-acquired images. After each brain was segmented from all non-brain tissue and reconstructed in three dimensions, its contours were traced on each coronal slice. The pons, medulla and much of the midbrain were excluded using a straight line connecting the two transverse fissures on each coronal slice where these structures were visible. The two hemispheres were separated. The cortex, including the hippocampus and the amygdala, was manually traced at the gray-white juncture on each individual section in both hemispheres throughout the brain and in all subjects. The central sulcus marked the posterior border of the frontal cortex on the dorsolateral surface. Whenever the central sulcus did not reach the Sylvian fissure, it was prolonged so as to intersect this fissure. The posterior end of the orbital and ventromesial frontal cortex was identified on the appropriate coronal section. On the mesial surface, the end of the central sulcus was connected, in a straight line, with the most posterior segment of the ventromesial cortex. Above the corpus callosum, this line was considered the posterior limit of frontal cortex on the mesial surface. These demarcations were applied in a consistent manner across all species.

In order to separate the precentral gyrus (mostly primary motor cortex, although intersubject variability is present²⁷) from the rest of frontal cortex, we used the precentral sulcus as its anterior limit. This separation was applied only on the hominoids (humans and apes) where, unlike the monkeys, the precentral sulcus is large and clearly present. Also, because of the quality of the scans in two of the four orangutan and one of the three bonobo brains, the identification of the precentral sulcus could not be achieved convincingly; thus, only two representatives of each of these species were included in the analysis of the two subdivisions of the frontal cortex, the cortex of the precentral gyrus and the frontal cortex anterior to the precentral sulcus. On the lateral surface, when the precentral sulcus was discontinuous, formed by two or more segments, those segments were connected with straight lines. The lateral and inferior end of the precentral sulcus was connected with the Sylvian fissure using a line perpendicular to this fissure. On the mesial surface, the end of the precentral sulcus was connected with a straight line to the junction between the cingulate sulcus and the posterior limit of frontal cortex.

K.S. identified the surface landmarks in consultation with H.D. The human, great ape and gibbon regions of interest (ROIs) were traced by A.L. and the monkey ROIs were traced by N.S. A reliability study was undertaken comparing the tracings of the cortex (chosen as the most arbitrary of the ROIs) by A.L. and N.S. to a sample of subjects traced by K.S. Five subjects (human, orangutan, gibbon, rhesus, cebus) were randomly chosen. Nonparametric correlation (Spearman's rho) between the results obtained by A.L. and K.S. was $r = 0.950$ ($p \leq 0.0001$) and that between NS and KS was $r = 0.9833$ ($p \leq 0.0001$).

The absolute volume of all sectors in both hemispheres was calculated using Brainvox. The volumes of the regions of interest were calculated from an automatic count of the number of voxels within a region multiplied by the volume of a single voxel in mm³. We calculated the total volume of the hemispheres, the total volume of the cortex of the hemispheres, and the volumes of frontal cortex, the cortex of the precentral gyrus and the rest of the frontal cortex.

We analyzed our data in terms of allometry by regressing the volume of the frontal cortex against the volume of the hemispheres minus the volume to be regressed. We did this because of concern raised in the literature

regarding the effects of regressing a large segment of the brain against the whole brain⁶. We fit a restricted-range log-log regression line through all primates excluding humans using least squares²⁸. We added the human values to the plot and compared expected versus observed values with respect to the regression line and the prediction interval (95%). A test of proportions was applied to evaluate the position of the human values with respect to the prediction interval. In addition to the least-squares analysis, we applied the reduced major axis as a best-fit line²⁹, and we found only minor differences in the relation between observed and expected values between the two approaches. We analyzed our data in both logarithmic and linear plots. The logarithmic transformation provides the best fit, as reflected in R^2 values that are closer to 1. We also calculated the size of the frontal cortex as a percentage of the volume of the hemispheric cortex. We used the same approaches to analyze our data on the precentral gyrus and the remaining portion of the frontal cortex.

Acknowledgements

We thank T. Wolfson and D. Politis for statistical consulting and J. Spradling and N. Xenitopoulos for technical and graphic support.

Competing interests statement

The authors declare that they have no competing financial interests.

RECEIVED 19 DECEMBER 2001; ACCEPTED 22 JANUARY 2002

1. Goldman-Rakic, P. S. The frontal lobes: uncharted provinces of the brain. *Trends Neurosci.* 7, 425–429 (1984).
2. Barbas, H. & Pandya, D. N. Architecture and intrinsic connections of the prefrontal cortex in the rhesus monkey. *J. Comp. Neurol.* 286, 353–375 (1989).
3. Fuster, J. M. *The Prefrontal Cortex. Anatomy, Physiology, and Neuropsychology of the Frontal Lobe* (Lippincott-Raven, Philadelphia, 1997).
4. Holloway, R. L. The evolution of the primate brain: some aspects of quantitative relations. *Brain Res.* 7, 121–172 (1968).
5. Jerison, H. J. in *Development of the Prefrontal Cortex: Evolution, Neurobiology, and Behavior* (eds. Krasnegor, N. A., Lyon, R. & Goldman-Rakic, P. S.) 9–26 (Brooks, Baltimore, 1997).
6. Deacon, T. W. *The Symbolic Species* (Norton, New York, 1997).
7. Brodmann, K. Neue Ergebnisse über die vergleichende histologische Lokalisation der Grosshirnrinde mit besonderer Berücksichtigung des Stirnhirns. *Anat. Anzeiger* 41, 157–216 (1912).
8. Blinkov, S. M. & Glezer, I. I. *Das Zentralnervensystem in Zahlen und Tabellen* (Fischer, Jena, 1968).

9. Uylings, H. B. M. & Van Eden, C. G. in *Progress in Brain Research* vol. 85 (eds. Uylings, H. B. M., Van Eden, C. G., De Bruin, J. P. C., Corner, M. A. & Feenstra, M. G. P.) 31–62 (Elsevier, New York, 1990).
10. Zilles, K., Armstrong, E., Schleicher, A. & Kretschmann, H. The human pattern of gyrification in the cerebral cortex. *Anat. Embryol.* 179, 173–179 (1988).
11. McBride, T., Arnold, S. E. & Gur, R. C. A comparative volumetric analysis of the prefrontal cortex in human and baboon MRI. *Brain Behav. Evol.* 54, 159–166 (1999).
12. Semendeferi, K., Damasio, H., Frank, R. J. & Van Hoesen, G. W. The evolution of the frontal lobes: a volumetric analysis based on three-dimensional reconstructions of magnetic resonance scans of human and ape brains. *J. Hum. Evol.* 32, 375–388 (1997).
13. Semendeferi, K. & Damasio, H. The brain and its main anatomical subdivisions in living hominoids using magnetic resonance imaging. *J. Hum. Evol.* 38, 317–332 (2000).
14. Semendeferi, K., Armstrong, E., Schleicher, A., Zilles, K. & Van Hoesen, G. W. Prefrontal cortex in humans and apes: a comparative study of area 10. *Am. J. Phys. Anthropol.* 114, 224–241 (2001).
15. Semendeferi, K., Armstrong, E., Schleicher, A., Zilles, K. & Van Hoesen, G. W. Limbic frontal cortex in hominoids: a comparative study of area 13. *Am. J. Phys. Anthropol.* 106, 129–155 (1998).
16. Damasio, A. R. *Descartes' Error* (Grosset/Putnam, New York, 1994).
17. Buxhoeveden, D. P., Switala, A. E., Roy, E., Litaker, M. & Casanova, M. F. Morphological differences between minicolumns in human and nonhuman primate cortex. *Am. J. Phys. Anthropol.* 115, 361–371 (2001).
18. Preuss, T. M., Qi, H. & Kaas, J. H. Distinctive compartmental organization of human primary visual cortex. *Proc. Natl. Acad. Sci. USA* 96, 11601–11606 (1999).
19. Zhang, K. & Sejnowski, T. J. A universal scaling law between gray matter and white matter of cerebral cortex. *Proc. Natl. Acad. Sci. USA* 97, 5621–5626 (2000).
20. de Winter, W. & Oxnard, C. E. Evolutionary radiations and convergences in the structural organization of mammalian brains. *Nature* 409, 710–714 (2001).
21. Finlay, B. L. & Darlington, R. B. Linked regularities in the development and evolution of mammalian brains. *Science* 268, 1578–1583 (1995).
22. Clark, D. A., Mitra, P. P. & Wang, S. S.-H. Scalable architecture in mammalian brains. *Nature* 411, 189–193 (2001).
23. Nimchinsky, E. A. *et al.* A neuronal morphologic type unique to humans and great apes. *Proc. Natl. Acad. Sci. USA* 96, 5268–5273 (1999).
24. Radinsky, L. The fossil evidence of anthropoid brain evolution. *Am. J. Phys. Anthropol.* 41, 15–28 (1974).
25. Damasio, H. & Frank, R. J. Three dimensional *in vivo* mapping of brain lesions in humans. *Arch. Neurol.* 49, 137–143 (1992).
26. Frank, R. J., Damasio, H. & Grabowski, T. J. Brainvox: an interactive, multimodal, visualization and analysis system for neuroanatomical imaging. *Neuroimage* 5, 13–30 (1997).
27. Roland, P. E. & Zilles, K. Brain atlases—a new research tool. *Trends Neurosci.* 17, 458–467 (1994).
28. Smith, R. J. Current events: regression models for prediction equations. *J. Hum. Evol.* 26, 239–244 (1994).
29. Aiello, L. C. Allometry and the analysis of size and shape in human evolution. *J. Hum. Evol.* 22, 127–147 (1992).