Brain development after birth differs between Neanderthals and modern humans

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Neanderthals had brain sizes comparable to modern humans, but their brain cases were elongated and not globular as in *Homo sapiens* [1,2]. It has, therefore, been suggested that modern humans and Neanderthals reached large brain sizes along different evolutionary pathways [2]. Here, we assess when during development these adult differences emerge. This is critical for understanding whether differences in the pattern of brain development might underlie potential cognitive differences between these two closely related groups. Previous comparisons of Neanderthal and modern human cranial development have shown that many morphological characteristics separating these two groups are already established at the time of birth [3-5], and that the subsequent developmental patterns of the face are similar, though not identical [6]. Here, we show that a globularization phase seen in the neurocranial development of modern humans after birth is absent from Neanderthals.

Comparing endocranial development between chimpanzees and modern humans from birth to adulthood, we have recently found that from the eruption of the deciduous dentition to adulthood the patterns of shape changes are remarkably conserved [7]. However, the developmental patterns differ markedly in the period directly after birth: within the first year of life, only modern human endocasts change rapidly from an elongated to a more globular shape. Notably, the shape changes during this 'globularization phase' in *Homo sapiens* seem to mirror the adult shape differences between brain cases of modern humans and Neanderthals. Our previous findings [7], therefore, highlight which ontogenetic mechanism could account for the adult endocranial shape differences between modern humans and our closest extinct relatives [2].

Here, we test whether we could find evidence for a globularization phase in the ontogenetic trajectory of Neanderthals, and thus whether the adult endocranial differences are already established at the time of birth, or develop later. We statistically compared shapes of virtual endocasts extracted from computed-tomographic scans of crania of 58 modern humans [7] and virtual reconstructions of 11 fossil humans, including the Neanderthal neonate Le Moustier 2.

Three lines of evidence suggest that Neanderthals did not have a globularization-phase after birth. First, both Neanderthal and modern human neonates have relatively elongated braincases at the time of birth (Figure 1A), but only modern human endocasts change to a more globular shape between dental age groups 1 and 2 (see Supplemental Information, published with this paper online). By contrast, the endocranial shapes of the two youngest Neanderthal specimens in our sample, the neonate Le Moustier 2 (dental age group 1) and Pech de l'Azé (dental age group 3), are so similar that their reconstruction distributions (which reflect the estimation uncertainty) overlap (Figure 1B). Second, if Neanderthals and modern humans had the same globularization-phase after birth, a Neanderthal neonate would need to have an extremely elongated neurocranium and a very poorly developed cerebellum (Supplemental Information). However, it is not possible to reconstruct the Neanderthal neonate Le Moustier 2 in a way that would match this prediction. Finally, given that large portions of the braincase of Le Moustier 2 had to be estimated (Figure 1A), we also conducted additional tests that did not rely on subadult fossils (Supplemental Information). We simulated the development of modern human neonates along the average human trajectory from age groups 2–6, thus skipping the globularization phase. The adult crania resulting from these simulations bear a striking resemblance to the Neanderthal average shape, even though they were based on modern human neonates.

We find that the modern human pattern of brain development is derived compared to Neanderthals. The pattern of endocranial shape changes between age groups 2 and 6 is similar among modern humans, Neanderthals and chimpanzees [7]. Neanderthals achieved endocranial volumes comparable to modern humans following this presumably ancestral pattern of development. Our results therefore provide an ontogenetic dimension to the findings of Bruner and colleagues [2]. This challenges the view that all morphological characteristics separating modern humans from Neanderthals are already established at the time of birth. However, our results are not incompatible with the findings reported by Ponce de León and colleagues [3-5]: when measurements of the face and neurocranium are analyzed together, the human and Neanderthal trajectories appear to be roughly parallel [3,4] because at the time of birth the face of a Neanderthal is already larger than that of a modern human (Figure 1A).

Our estimates of the endocranial capacity of Le Moustier 2 (408-428 cc) are similar to those reported for the Neanderthal neonate from Mezmaiskaya [4] and corroborate the finding that brain volume around the time of birth was similar in Neanderthals and modern humans [4,5]. Our virtual reconstructions also confirm that many facial characteristics that separate Neanderthals from modern humans, in particular the size of the face relative to the braincase, are established prenatally [3-5]. However, most endocranial shape differences develop postnatally. Around the time of birth, modern humans and Neanderthals have similar endocranial sizes and shapes, with Neanderthals only being slightly more elongated than modern humans (Figure 1). After the constraints on neonatal shape and size imposed by the shape of the birth canal of the female pelvis [4,5,8] are relaxed, the two species develop along different pathways.

The difference between the developmental patterns of modern humans and Neanderthals is most prominent directly after birth, when the shape of the vault is extremely sensitive to the tempo and mode of brain growth [7]. When the cranial bones are thin and not yet fully ossified, the shape changes of the frontal and parietal bone are largely driven by the increase in brain volume. While the growth of the face affects the shape of the cranial base [6,7], it is unlikely that this alone could explain the shape changes of the parietal and occipital bone shown in Figure 1. We suggest, therefore, that species

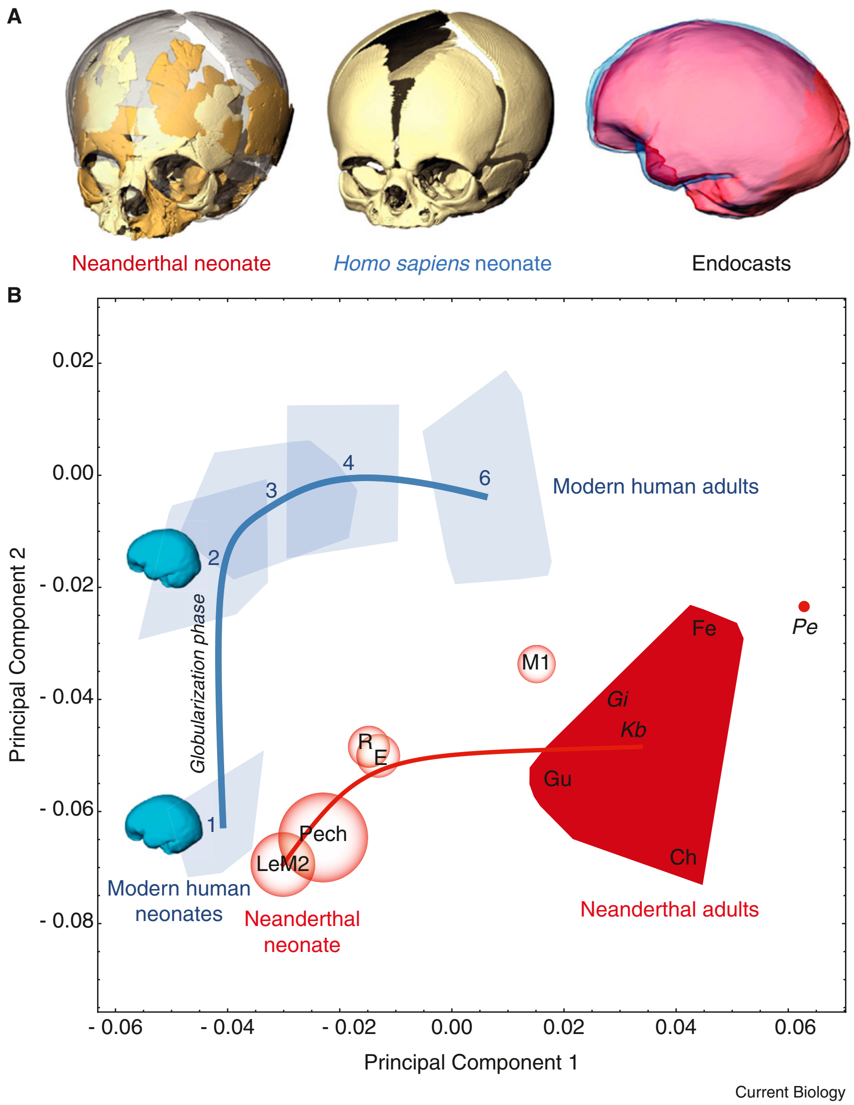

Figure 1. Neanderthal and modern human brains grow differently.
(A) For the virtual reconstruction of the Neanderthal neonate Le Moustier 2, CT scans of individual fragments were assembled on the computer. Fragments that were mirror-imaged to the other side are plotted in a darker shade. The gray surface represents estimated missing data. At birth, Neanderthals and modern humans have very similar endocranial volumes and shapes (red: Le Moustier 2; blue: modern human). (B) A principal component analysis of endocranial shape changes from birth (age group 1) to adulthood (age group 6). The convex hulls for modern humans (blue) are based on dental age groups. The fossil convex hull (red) is based on the Neanderthal adults only. The average developmental trajectory is plotted as a solid line. Endocranial mean shapes visualize the shape change during the modern human globularization phase between age groups 1 and 2. All fossils were reconstructed multiple times; each distribution of reconstructions falls within the respective semitransparent disks (Neanderthal specimens: LeM2 — Le Moustier 2; Pech – Pech de l'Azé; R – Roc de Marsal; E – Engis 2; M1 – Le Moustier 1; Gu – Guattari; Fe – La Ferrassie 1; Gi – Gibraltar; Ch — La Chapelle-aux-Saints. Archaic *Homo*: Kb — Kabwe; Pe — Petralona).

differences in brain growth rates [4,5] and timing underlie the uniquely modern human globularization phase.

The development of cognitive abilities during individual growth is linked to the maturation of the underlying neural circuitry: in humans, major internal brain reorganization has been documented until adolescence, and even subtle alterations of pre- and perinatal brain development have been linked to changes of the neural wiring pattern that affect behavior and cognition [9]. The uniquely modern human pattern of early brain development is particularly interesting in the light of the recent breakthroughs in the Neanderthal genome project [10], which identified genes relevant to cognition that are derived in living humans. We speculate that a shift away from the ancestral pattern of brain development occurring in early *Homo sapiens* underlies brain reorganization and that the associated cognitive differences made this growth pattern a target for positive selection in modern humans.

Supplemental Information

Supplemental Information including experimental procedures, supplemental results and two figures can be found with this article online at doi:10.1016/j.cub.2010.10.018.

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References

1. Lieberman, D.E., McBratney, B.M., and Krovitz, G. (2002). The evolution and development of cranial form in *Homo sapiens*. Proc. Natl. Acad. Sci. USA *99*, 1134–1139.
2. Bruner, E., Manzi, G., and Arsuaga, J.L. (2003). Encephalization and allometric trajectories in the genus *Homo*: evidence from the Neandertal and modern lineages. Proc. Natl. Acad. Sci. USA *100*, 15335–15340.
3. Ponce de León, M.S., and Zollikofer, C.P. (2001). Neanderthal cranial ontogeny and its implications for late hominid diversity. Nature *412*, 534–538.
4. Ponce de León, M.S., Golovanova, L., Doronichev, V., Romanova, G., Akazawa, T., Kondo, O., Ishida, H., and Zollikofer, C.P. (2008). Neanderthal brain size at birth provides insights into the evolution of human life history. Proc. Natl. Acad. Sci. USA *105*, 13764–13768.
5. Zollikofer, C.P., and Ponce de León, M.S. (2009). The evolution of hominin ontogenies. Semin. Cell Dev. Biol. *21*, 441–452.
6. Bastir, M., O'Higgins, P., and Rosas, A. (2007). Facial ontogeny in Neanderthals and modern humans. Proc. Biol. Sci. *274*, 1125–1132.
7. Neubauer, S., Gunz, P., and Hublin, J.J. (2010). Endocranial shape changes during growth in chimpanzees and humans: a morphometric analysis of unique and shared aspects. J. Hum. Evol. *59*, 555–566.
8. Weaver, T.D., and Hublin, J.J. (2009). Neandertal birth canal shape and the evolution of human childbirth. Proc. Natl. Acad. Sci. USA *106*, 8151–8156.
9. Courchesne, E., and Pierce, K. (2005). Brain overgrowth in autism during a critical time in development: implications for frontal pyramidal neuron and interneuron development and connectivity. Int. J. Dev. Neurosci. *23*, 153–170.
10. Green, R.E., Krause, J., Briggs, A.W., Maricic, T., Stenzel, U., Kircher, M., Patterson, N., Li, H., Zhai, W., et al. (2010). A draft sequence of the Neandertal genome. Science *328*, 710–722.

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