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Patterns In Palaeontology: Digitally Peering Inside Fossil Skulls

by Charlotte M. Bird [1]

Introduction:

Imagine you are an avid fossil hunter and have just dug up a skull of an extinct vertebrate. You are the first human ever to see it. Not only is that amazing, but you are also at the start of a journey into discovering how this organism lived: whether it was diurnal (active during the day) or nocturnal, whether it hunted above ground or burrowed, had poor vision or an exceptional sense of smell. Despite the millions of years that may have passed, the growing field of virtual palaeontology provides a new world of analysis techniques that can help palaeontologists to peer inside the skull and uncover some truly fascinating insights.

What are digital endocasts?

Virtual Palaeontology is the non-destructive study of fossils using digital methods, enabling, for example, both analyses of external skull features, alongside identification of internal structures in the form of digital cranial endocasts (3D models depicting the skull interior).

For the creation of digital endocasts, computed tomography (CT) scans of fossils (comprised of potentially thousands of images of thin slices through it) are used. These pictures are loaded into imaging software such as Avizo or SPIERS. In the programme all parts of the images that are lighter than a certain level are marked as part of the skeleton, and all parts that are darker as sediment fill. This process, known as thresholding, is then applied to the image stack to separate skeletal elements from sediment. Coloured masks are then added by filling in the cavities containing the feature of interest (think paint-by-numbers, but a little more scientific, Fig. 1). Through editing the stack image-by-image, the changing shape of anatomical features can be defined, producing 3D models of the brain, inner ear and neurovascular anatomy, for example. Once you have 3D models of desired anatomical structures ... let the research commence! From simple anatomical descriptions and comparisons with extant (living) relatives to the frequency of sounds it could hear or its relative level of intelligence (and how this changed over the evolution of the fossil group), the analytical world is your oyster.

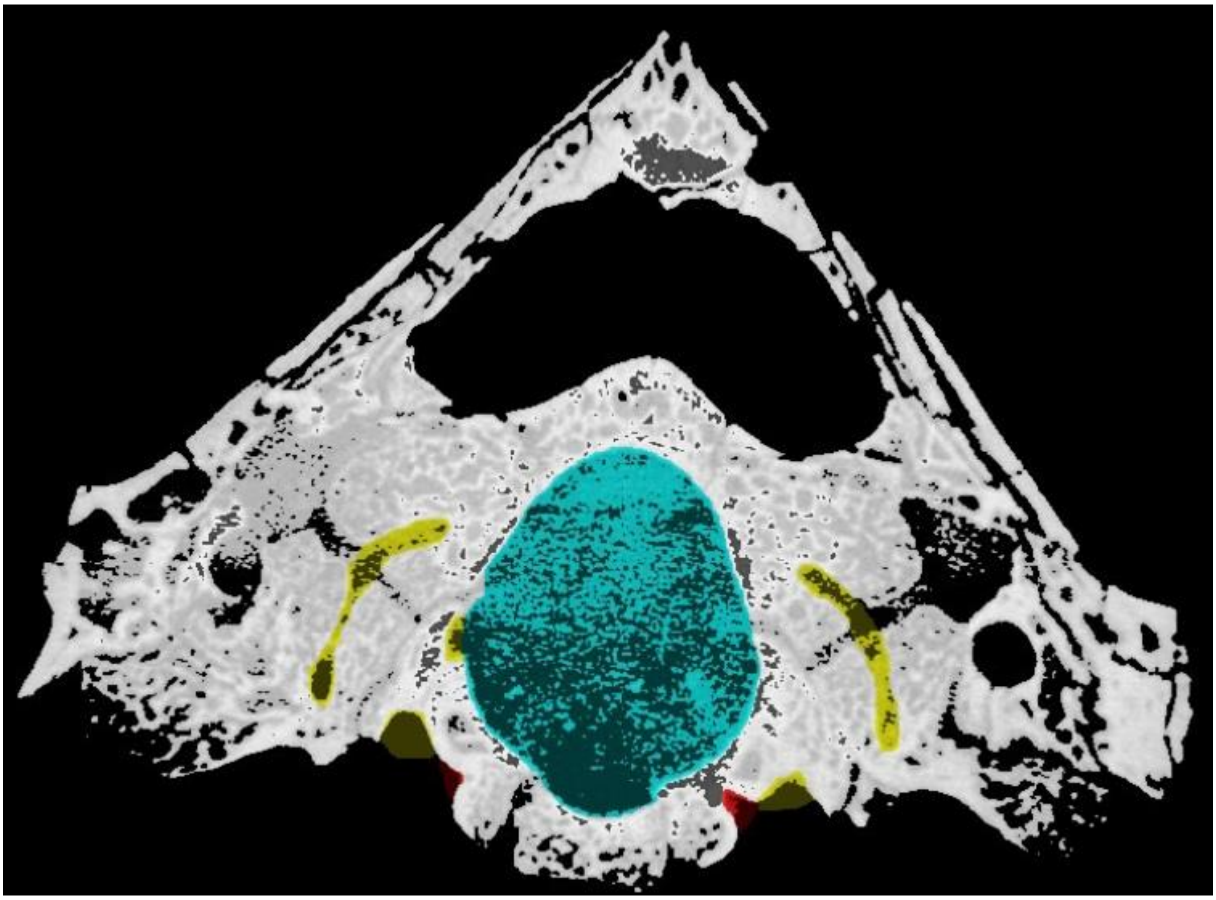

Figure 1 — Example mask for the skull of a fossil reptile called a cynodont, with the brain defined in blue, inner ear in yellow and the neurovascular system in red. Sediment infill is clearly observed in the brain mask. Author's own work.

What can cranial endocasts tell us?

To put endocasts into context, a recent study considered the changing endocranial anatomy of the skulls of cynodonts, a group of therapsids (fossil reptiles) that appeared during the late Permian period (around 259 million to 252 million years ago) and expanded during the Triassic period (252 million to 201 million years ago), with one branch leading to modern mammals. Understanding how the brain of mammals evolved from those of primitive cynodonts, developing the ability to carry out the complex functions that make modern mammals distinct, is of great importance to palaeoneurology — a field of research that has focused on the evolution of the human brain from those of our primate ancestors.

3D models of cynodont brains (Fig. 2) enable palaeontologists to describe new aspects of the anatomy of little-known species, such as *Thrinaxodon liorhinus*, allowing them to identify anatomical (and potential functional) changes in cranial features in the mammalian lineage. However, the most exciting revelations come from quantitative analyses, in which linear and volumetric data of the shapes and sizes of anatomical features can shed light upon a species' senses, and possibly help researchers to observe differences between members of the same species (intraspecific changes) and during the life cycle of an individual (ontogenic changes). In turn, this may indicate variations in mode of life. Other methods of analysis include:

- 3D point cloud analysis in CloudCompare, which uses a colour scale to map variations in shape between 3D models, allowing for variations in brain shape to be identified and mapped.

- Calculation of encephalisation quotients, in which brain volumes determined from the 3D models are used to estimate a relative level of cognitive ability (intelligence) for a species relative to other species through time. Higher encephalisation quotient values are associated with social interactions and foraging behaviour, so the quotient offers information about ways of life.
- Assessing hearing capability, or auditory acuity, which can be assessed through measurements of the length of a cavity in the inner ear called the cochlea.
- Measuring the shape and size of semi-circular canals of the inner ear, which provide information on an individual's agility, once more indicating behavioural patterns.

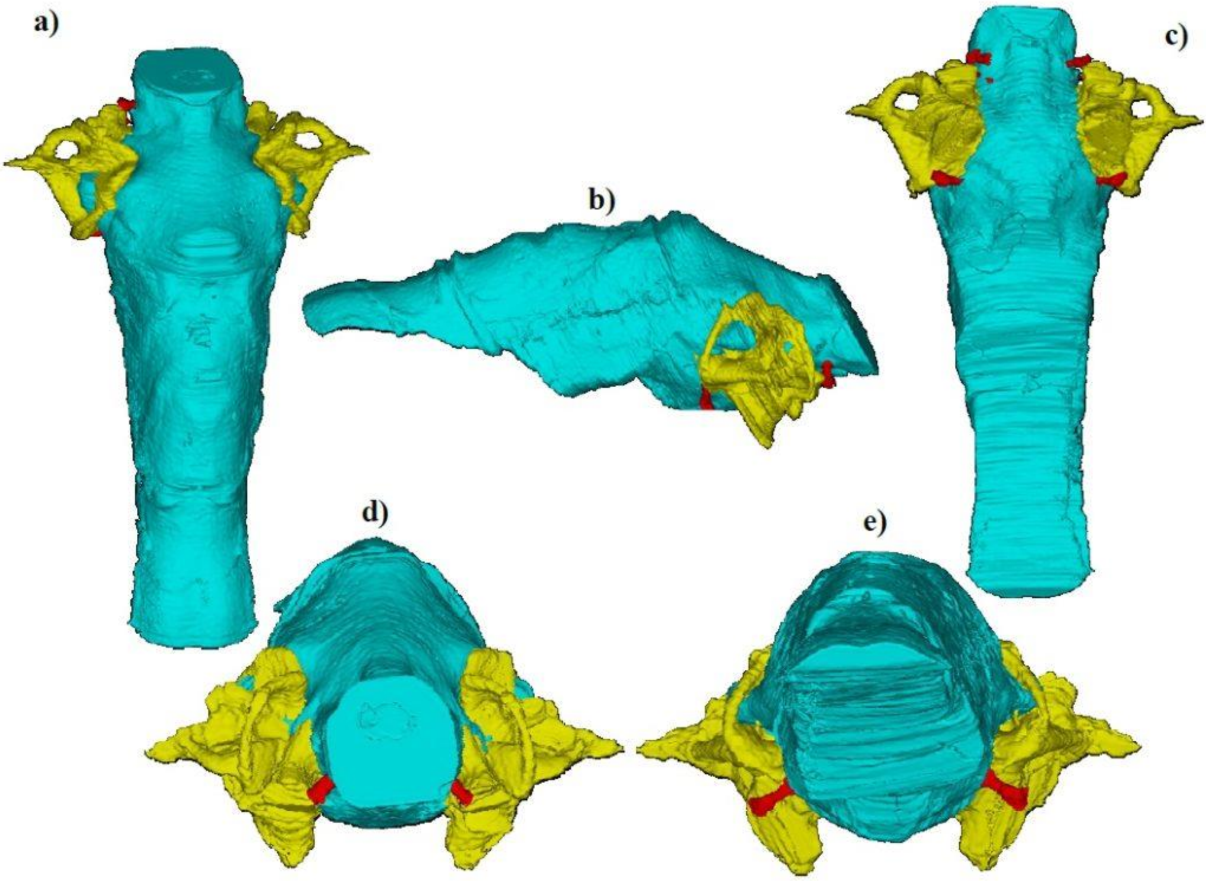

Figure 2 — Full endocast reconstruction for *Thrinaxodon liorhinus* (specimen UMZC T815) depicting the brain (blue), inner ear (yellow) and neurovascular anatomy (red). (a) Dorsal/top view. (b) Lateral/side. (c) Ventral/bottom. (d) Posterior/back. (e) Anterior/front. Brain length is 36.80 mm; maximum width is 15.40 mm. Author's own work.

From an in-depth study of cranial endocasts, three stages of development have been identified in the mammal brain over time (Fig. 3). First, development of body hair led to increased tactile sensitivity and olfactory acuity (sense of smell) from whiskers (processed by the brain). A secondary improvement in olfactory capabilities produced an observable increase in brain size. A third pulse in development occurred due to changes in the nasal cavity, ultimately leading to enhancement of hunting abilities.

Endocasts are pretty great ...

You can access your specimens anywhere in the world, at any time, as long as you have your data sets. Digital reconstruction saves your data for the future, in case the original specimen is lost or damaged. CT scanning the fossil also means that you do not have to destroy the original by grinding away thin layers to take photographs of cross-sections to make a 3D model. More importantly, however, cranial endocasts help to overcome some of the bias in the fossil record. Soft tissues are rarely preserved, yet can provide some of the most pivotal information about form, function and mode of life for extinct organisms. Based on the assumption that the brain followed the shape of the brain case, the soft tissues of the endocranial cavity can be reconstructed, with only the meninges (three layers of protective tissue) known to also fill the cranial cavity in modern mammals. Furthermore, image thresholding on the CT scans enables digital density filtering – separating fossil structures from obstructive sediment infill, giving a clearer picture of the internal features than visual inspection offers. Therefore, digital reconstruction techniques are paramount to understanding more about functional morphology than the fossils themselves can offer from a skeletal perspective.

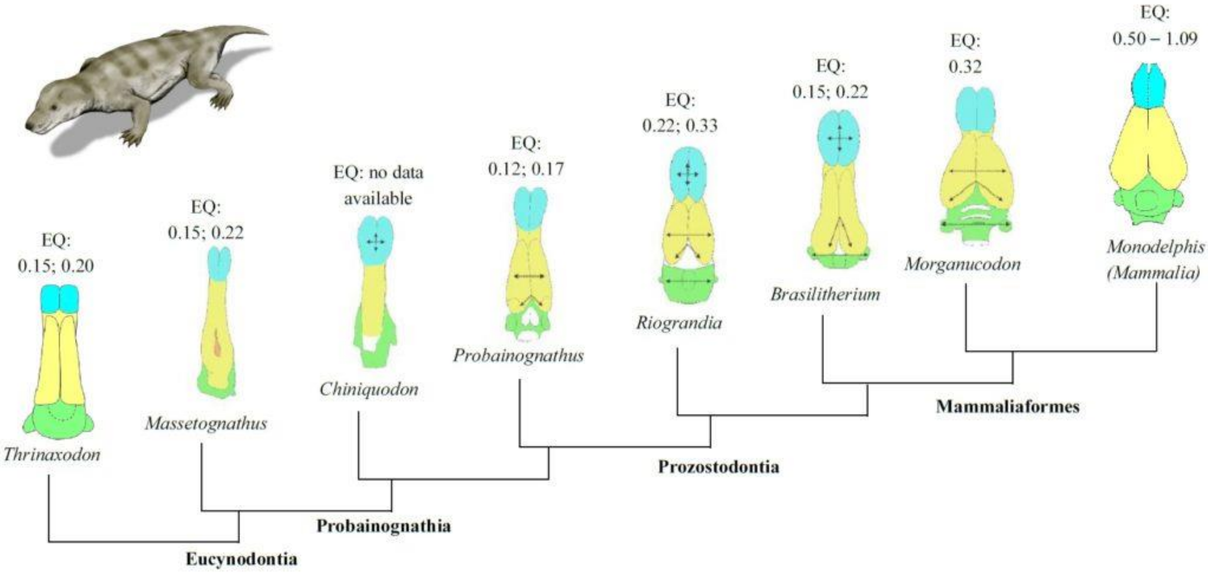

Figure 3 — Schematic representation of changes in cynodont brain morphology through time, alongside calculated encephalisation quotients. (Figure modified from Rodrigues et al., 2018). Inset: *Thrinaxodon liorhinus* (Image by Nobu Tamura. Licensed under CC BY-SA 2.5via Wikimedia Commons).

... But they have their limitations

Despite endocasts, and virtual palaeontology itself, providing fantastic leaps forward in fossil research, digital reconstructions do have some limitations. First, the assumption made during endocast creation that the intracranial space correlates directly with the original soft-tissue structures of the brain is problematic. Modern mammals additional fluid and tissues in the intracranial space (for example, meninges, blood vessels and nerves). The external surface of the mammal brain is also known to be convoluted with ridges (gyri) and grooves (sulci), but no direct impression of this can be discerned on the braincase. , palaeoneurological studies are limited to external features of the endocasts. 3D models do not provide any direct information about the brain’s internal structures (such as neuron morphology, density and connectivity) — the perils of working with fossils.

Furthermore, the fossilisation process itself causes a bias in the types of endocast that can be produced. Skulls are often deformed or fragmented, and broken pieces can become offset. As a result, only a few specimens are preserved well enough to produce useful endocasts, and palaeoneurological studies have to rely on small data sets. The individual animals can affect 3D models, too: juveniles, for example, often don't have fully ossified skulls (particularly, they have insufficient bone growth associated with the inner ear) and thus parts of the braincase are absent, hindering reconstruction efforts to fully constrain cranial features. Similarly, some parts of the skull never become ossified, with no bones confining the base of the brain and olfactory bulbs (Fig. 4), causing difficulties in defining neurovascular anatomy and how far the olfactory bulbs extend. This also results in underestimates of brain volumes, as the full depth of the brain within the skull cannot be determined. This, in turn, affects quantitative analyses, including calculation of encephalisation quotients. However, the bias in this volumetric analysis can be reduced by morphological comparison with the brain of an extant relative (such as *Monodelphis domestica*, the grey, short-tailed opossum) to define the brain shape. The model can also be compared with models from other cynodonts to determine the shape of the olfactory bulbs, inferring the symmetrical morphology of later cynodonts onto the poorly reconstructed olfactory bulbs of their predecessors.

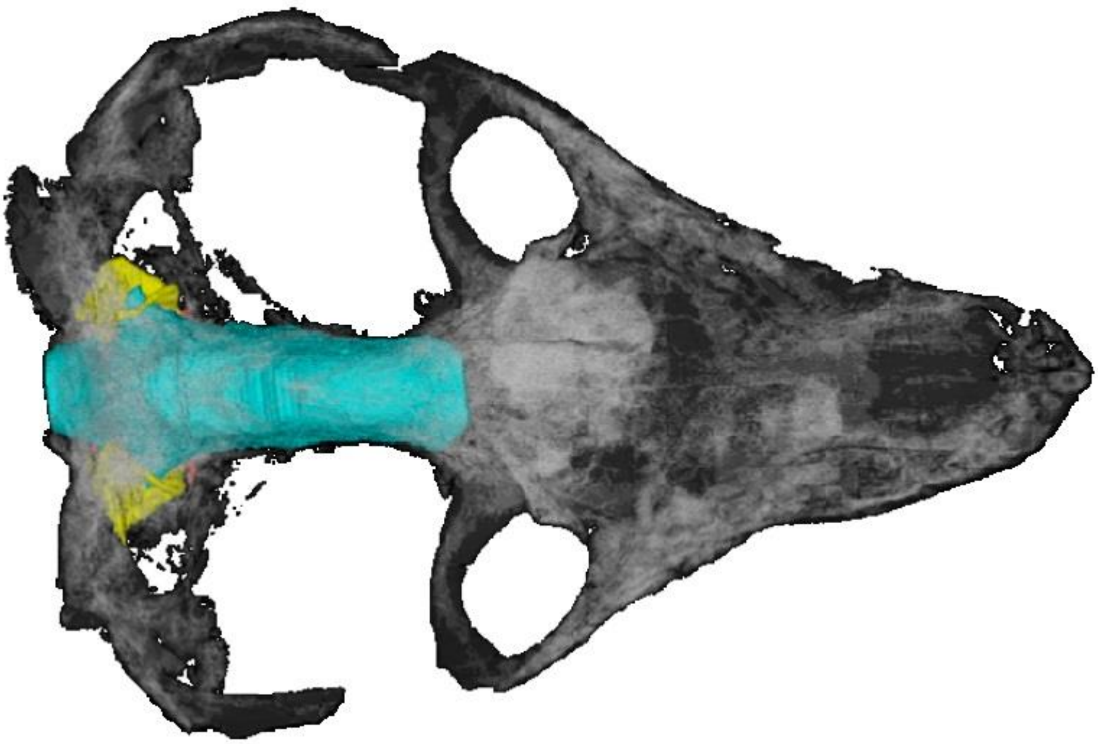

Figure 4 — *Thrinaxodon* skull (specimen NHMUK PV R 511) displaying truncated olfactory bulbs between the eye sockets. The placement of the brain, inner ear and neurovascular structures are also shown. Skull length 69 mm. Author's own work.

Technology itself can be a problem. Standard CT scanning takes images using X-rays; these have fairly low resolution, so it can be difficult to see fine detail. Fossils scanned with micro-CT will produce much higher resolution images than X-ray scanning, making the former preferable for acquiring fine detail data sets to study.

And finally, the biggest limitation to endocasts can be the researcher. Everyone has their own opinions on what they are looking at, depending on prior knowledge, which ultimately affects what is included within the mask that defines the model. Small differences during endocast construction could lead to potentially significant morphological and volumetric discrepancies, affecting all subsequent analyses. The specimens chosen for study could limit your findings if they are all of a similar age range, hampering any chance of identifying ontogenetic variation. Small sample sizes also prevent discovery of possible intraspecific variation. Additionally, although digital studies hold many advantages, there is nothing quite like getting up close to a fossil and really getting to see all of the curiosities it has to offer.

Conclusions

Endocasts are invaluable to reconstructing soft tissues lost to time, and to inferring how these anatomical features may have impacted the manner in which the individual lived, and how behavioural patterns may have changed during the evolution of a species or a larger part of the mammalian lineage. 3D models provide the closest possible approximation palaeontologists can obtain of what lay beneath the surface of fossil skulls, and provide valuable information on the development of the mammalian brain through time. Moreover, cranial endocasts offer possibilities for determining how sensory capabilities impacted upon the size and shape of various brain regions.

Whilst reconstruction and analysis methods have their limitations, further research will continue to fine-tune these methods, providing an exciting future for the emerging field of virtual palaeontology — aiding not only fossil studies, but also public engagement with scientific research.

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