

The origin of the neocortex

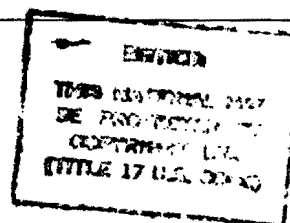
John Allman

The neocortex is a layered sheet of neurons in the dorsal forebrain of mammals. Like fur, it is uniquely mammalian. My conjecture is that neocortex, like fur, keeps the body warm. A mammal requires 5 to 10 times more energy expenditure than does an equivalently sized reptile. Most of this increased energy expenditure is devoted to the homeostatic mechanisms of thermoregulation. Thus mammals must eat a great deal more than reptiles to avoid starvation. My hypothesis is that neocortex evolved in tandem with endothermy to assure the reliable and continuous localization of food resources. The neocortex consists largely of topographically organized maps of vision, touch and hearing that store representations of the mammal's interactions with its environment. The neocortical network requires an initial period of training, which is manifested in infant play behavior. During this training period the infant's energy requirements are provided by its mother's milk. Thus mammalian lactation and play behavior are necessary adaptations to support linked endothermic and neocortical homeostatic mechanisms.

Key words: neocortex / evolution / metabolism / homeostasis

THE NEOCORTEX is a layered sheet of neurons in the dorsal forebrain that is unique to mammals. My purpose is to explore how the origin of neocortex might have been linked to the emergence of other aspects of mammalian biology based on the fossil record and the anatomy and physiology of living animals. The neocortex originated between 160 and 300 million years ago. Since neocortex is present in all mammals it was very likely present in the most recent common ancestor of all living mammals, which lived between 160 and 240 million years ago.^{1,2} Since the neocortex is not present in reptiles or amphibians, it must have developed after the divergence of the line leading to mammals from the earliest reptiles, which occurred about 300 million years ago.¹

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1044-5765/90/0204-0002\$5.00/0*



The origin of mammals

Pelycosaurs experiment with temperature homeostasis

The oldest fossil reptiles come from the early Pennsylvanian Period locality of Joggins, Nova Scotia.¹ These 300 million-year-old rocks contain the earliest pelycosaurs, which belong to the line leading to mammals, and the earliest captorhinomorphs, which belong to the line leading to the living reptiles and birds.¹ The pelycosaurs were very successful both as carnivores and herbivores during the Permian. They evidently were experimenting with temperature homeostasis since some of them possessed tremendously elongated vertebral spines that in life bore a vascularized dorsal 'sail' that could have increased the rate of heat exchange with the environment,³ serving as a solar collector in the morning and a radiator of excess heat during periods of intense activity. This homeostatic mechanism would have enabled them to become active several hours earlier in the day and to sustain intense exertion for longer periods.⁴

There are three main advantages for an animal to maintain a relatively constant body temperature: ecological, neurobiological and biochemical. First, temperature homeostasis enables the animal to be active over a broader range of environmental temperatures. Second, constant body temperature facilitates constancy in neural function. For example, in ectotherms the tuning curves of auditory neurons vary with temperature⁵ which complicates the neural reconstruction of the sensory world. Third, temperature homeostasis provides profound biochemical advantages.^{6,7} Each of the chemical reactions in the body has a biochemically optimum operating temperature that is the joint product of chemical efficiency and the requirements of regulation. The molecular structure of the enzymes catalyzing and regulating these reactions evolved under conditions governed by body temperature. The structure and function of these enzymes can be much more precisely tuned by evolutionary processes for a constant body temperature than for a broad range of temperatures.

Active cynodonts

The pelycosaurs gave rise to the therapsids, which were among the most successful land animals of the late Permian and early Triassic. The therapsid family of cynodonts, 'dog-toothed' carnivores, contained the direct ancestors of mammals. In addition to canine teeth for seizing and piercing prey, they possessed incisors for cutting and molar-like teeth for grinding the prey in preparation for digestion. The presence of these mammal-like dental specializations suggest that the cynodonts may have had an elevated rate of metabolism, since chewing food prepares it for more rapid digestion and energy delivery than occurs in living reptiles. The cynodonts also had a bony secondary palate that enabled them to chew and breathe simultaneously, another specialization necessary for an elevated, aerobic metabolism.¹ They had longer, more graceful limbs that supported their bodies from below rather than the typical, reptilian sprawl. Their posture and their mammalian type of ribcage also suggest a more active, aerobic metabolism.⁸ The discovery of a tiny cynodont skeleton nestled with an adult suggests that the cynodonts cared for their offspring.⁹

The earliest mammals were tiny

The earliest true mammals first emerged from the cynodont stock in the late Triassic, about 220 million years ago. They were more than two orders of magnitude smaller than the average cynodont: *Eozostrodon* weighed only about 30 g.¹ Their cynodont ancestors evidently were already committed to a high energy life style. If these early mammals were endothermic, their extremely small size and large surface-area-to-volume ratio (with consequent increased metabolic heat dissipation) would have forced them into a constant struggle to avoid starvation.

Two features of the skull mark their status as true mammals. First, two bones that originally were part of the lower jaw, the quadrate and the angular, became the malleus and incus, ossicles that together with the stapes, form the sound-conducting chain in the mammalian middle ear. This adaptation may be responsible for ability of mammals to hear much higher frequencies than birds or reptiles and may have served as a means for identifying distressed infants that emitted high pitched cries.¹⁰ Second, the cusp patterns of the upper and lower molar teeth intermesh in precise occlusion, thus increasing the

efficiency of mastication to prepare the food for even more rapid digestion and energy delivery to the organism.¹¹ The earliest mammals, like most living mammals, had only two sets of teeth, deciduous and permanent, whereas their cynodont ancestors, like most reptiles, continuously replaced teeth throughout life.¹¹ The stabilization of tooth development in the permanent dentition of the early mammals probably provided greater precision in dental occlusion than could be achieved with continuously replaced teeth in cynodonts.

The early mammals are examples of pedomorphic evolution¹² in that they were tiny versions of their cynodont ancestors in which development was arrested. This loss of morphological plasticity associated with the truncation of development in the early mammals may have been compensated by increased neural and behavioral plasticity arising from the formation of neocortex.

Energetic and regulatory costs of endothermy

Mammals expend five to ten times more energy than the same-sized reptiles, necessitating a comparable increase in food intake;¹³ this elevated requirement may be more than doubled in lactating mothers in small species.¹⁴ These developments required the ability to find large amounts of food on a reliable basis. Since the early mammals were very small, their capacity to store energy in fat was severely limited and they faced the continuous prospect of starvation. I think that neocortex emerged as a homeostatic mechanism linked to endothermy that enabled mammals to map the food resources in their environments and to develop foraging strategies for obtaining those resources on a reliable and continuous basis.

Mapping the environment in neocortex

An animal's natural environment is inherently noisy, complex and ambiguous. The neocortex enables mammals to resolve the structure within the noisy sensory array so that recurrent 'images' from the habitat are readily perceived and placed in the correct spatial context. This process requires substantial learning, and the storage of the learned information probably occurs in part within the topographically organized neocortical areas. I am not suggesting that there exists anything like a topographic map of the

animal's habitat within its neocortex but rather that cortical topography greatly facilitates both the resolution of complex structure within the habitat and recovery of that solution when that same structure is re-encountered by the mammal. The net effect is to enable the mammal to resolve the physical complexities of its environment such that it can regularly find sufficient food to support the elevated energy requirements necessary for temperature homeostasis.

Maps are a basic feature of neocortical organization

Much of the neocortex is devoted to topographic representation of the senses through which we perceive the external world: vision, touch and hearing. The available comparative data on neocortical mapping from mammals that retain many primitive features, such as monotremes, didelphid marsupials and eutherian insectivores, indicate that these maps probably were present in the early mammals. Recently, my colleagues and I¹⁵ have mapped the sensory areas in the neocortex of *Monodelphis*, a member of the family of didelphid marsupials. The skeletons of these mammals retain the primitive features of the early marsupials that lived during the Cretaceous period nearly 100 million years ago when the dinosaurs still roamed the Earth.¹⁶ More than 75% of the neocortex in *Monodelphis* is devoted to topographically organized sensory maps. The position and internal organization of these maps closely resembles the maps obtained from the neocortex in the hedgehog by Jon Kaas and his collaborators.¹⁷ These findings suggest that this form of neocortical mapping is at least as old as the common ancestor of marsupial and eutherian mammals. There is less evidence available from monotremes, but it is known that the somatosensory neocortex of the platypus contains an exquisite representation of its sensitive bill.¹⁸ In sum, these data suggest that sensory maps are an ancient feature of neocortical organization.

There is no evidence that any forebrain cortical structure outside the neocortex contains topographic maps. Thus, the topographic mapping of vision, touch and hearing may have developed at the origin of neocortex. The cortical structures of the forebrain are characterized by a sheet-like architecture in which the principal neural components are pyramidal neurons with radially oriented apical dendrites. The neocortex is characterized by multiple layers of

neurons, each with specific input and output. The non-neocortical forebrain cortex, which possesses simpler neuronal layering, includes the olfactory cortex, the hippocampus and the reptilian 'general' cortex, none of which are known to contain topographic maps.

Non-classical receptive fields in space and time

It has been conventional to believe that the basic function performed by neurons within the topographically mapped neocortical areas is the extraction of some perceptually salient aspect of the stimulus within a restricted receptive field. However the *true receptive field* for most visual cortex neurons is very much larger than the *classical receptive field* as defined by the conventional mapping methods of presenting a stimulus on a featureless background.^{19,20} The true receptive fields are mapped by the interaction of stimuli presented simultaneously outside the classical receptive field with stimuli presented within it. The large non-classical receptive fields are ideally suited to perform spatially integrative functions of local-global synthesis, such as the perceptual constancies of color, motion and space, and the discrimination of figures from the background.

I believe that the non-classical receptive fields may integrate across time as well as space and that certain kinds of long-term memory are embedded within the topographically mapped neocortical areas in a manner analogous to that in which global spatial information is embedded. While I do not have any direct evidence for this proposition, there are several lines of indirect evidence. In tests with Gollin figures, which are a graded series of pictures of an object of varying degrees of completeness, amnesic patients learn to identify pictorial figures on the basis of very incomplete samples.²¹ The classic amnesic patient, HM, whose medial temporal lobe structures were removed for treatment of epilepsy but whose lateral neocortical visual areas are intact (see Damasio and Damasio, this issue²²) showed substantial learning in his ability to identify incomplete figures even though he could not remember when retested that he had ever seen the figures before.²³ These memory effects may be related to the 'perceptual representational system' revealed by priming experiments and postulated to reside in posterior neocortex.²⁴

The priming memory effects are very dependent on spatial orientation, which suggests that they are performed within topographically mapped areas.

Similar effects have been observed in learning to see complex random-dot stereograms that may involve the neocortical visual areas.²⁵ The hypothesis that the non-classical receptive fields participate in learning to see complex figures could be tested by presenting to a visual cortical neuron a stimulus made up of a figure embedded in noise and retesting the neuron with the same stimulus after revealing the hidden figure. I predict that some visual cortical neurons will respond to cognitively defined contours in a manner analogous to the responses of some to 'illusory' contours.²⁶

Resolving an ambiguous world

I believe that the first problem that the neocortex must solve is the extraction of figures from a noisy and ambiguous sensory array. This process requires considerable computation. The solutions are achieved within a topographic context and the topographic order of the neocortical maps may greatly facilitate these solutions. This may be the basic reason why so much of neocortex is topographically organized. The effect is illustrated in Figure 1, which appears on initial inspection to be nothing but noise. Repeated inspection reveals the presence of a dog. The successful resolution of such a noisy figure probably depends on getting a correct interpretation of some

part of the figure and spatially propagating the solution to encompass the whole figure. The spatial propagation within feature space may involve an underlying propagation within a neocortical map. Once the solution is achieved it is probably permanently stored, at least in part, in topographically mapped neocortical areas, thus enabling the rapid resolution of the structure of the environment even though the relevant features are embedded in noise and ambiguity.

Neocortex, lactation and play

Mammals expend most of their energy maintaining a constant body temperature.²⁷ Young reptiles function as miniature versions of adults but baby mammals are dependent because of their poor capacity to thermoregulate, which is a consequence of their need to devote most of their energy to growth. This dependency is satisfied in mammals by maternal care, shelter, warmth and milk. During the period of infant dependency, baby mammals play, which may be crucial for the development of the neocortex. The baby mammal's playful interaction with its environment serves to provide the initial training for the neocortical networks that ultimately will enable the animal to localize, identify and capture resources in its environment. In humans,

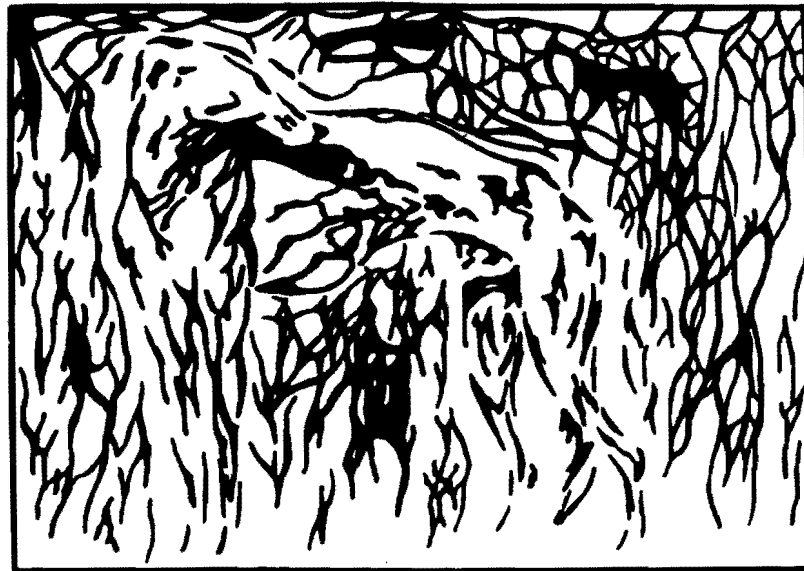


Figure 1. A figure of a dog embedded in a noisy environment. Reproduced from C. M. Mooney, Closure Test, McGill University, Montreal.

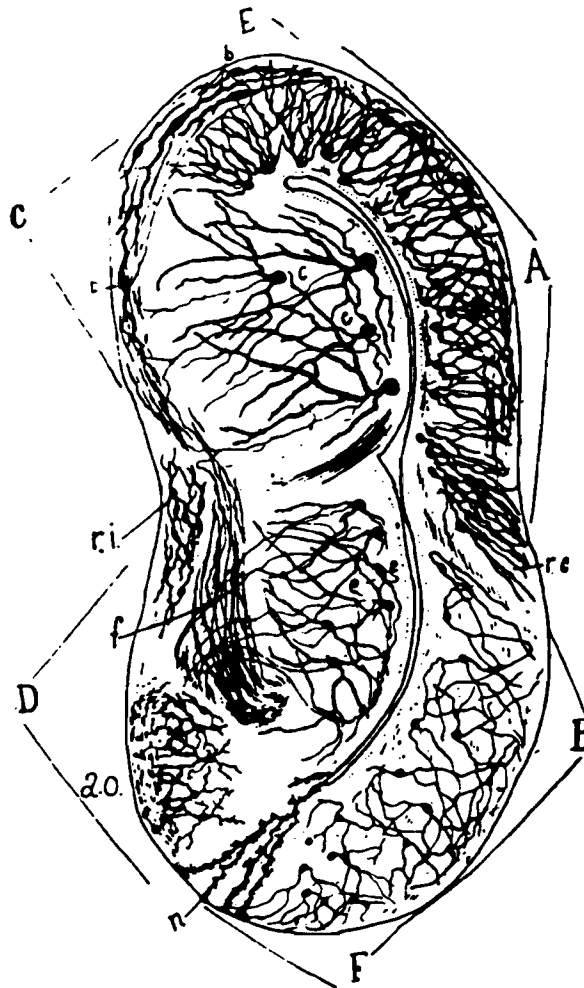


Figure 2. Golgi-stained coronal section through the right half of the telencephalon of a frog. A, external cortex; B, basal ganglia; C, fornix; D, septum. The external cortex consists mainly of a single layer of pyramidal cell bodies with their apical dendrites oriented radially toward the outer surface of the brain. The neocortex may have emerged from a region in an ancestral amphibian corresponding to a portion of the external cortex by the addition of cellular layers and topographically organized connections with the thalamus. Reproduced from ref 28. Dorsal is up; lateral is to the right.

this playful interaction persists into adulthood, which might be another example of pedomorphy¹² in our evolutionary history.

The structural derivation of neocortex

Since the line leading to mammals diverged from the line leading to reptiles and birds very soon after the origin of amniotes 300 million years ago, the most appropriate living model for the organization of the precursors of neocortex is to be found in the forebrain of amphibians rather than reptiles. As can be seen

in Figure 2, taken from the Golgi study of the frog brain by Pedro Ramon y Cajal,²⁸ most of the neurons in the dorsal telencephalon are pyramidal cells with their apical dendrites oriented toward the surface of the brain. The apical dendrites typically span the vertical dimension, or thickness, of the cortex and this basic architectural feature may constrain the organization of forebrain cortical structures into sheets. The transformations necessary to produce neocortex in the line leading to mammals could have resulted from changes in the regulation of neuronal proliferation and migration, leading to the

production of additional cortical layers. The precursor of neocortex in the ancestral amphibian may have corresponded to a portion of the dorsolateral cortical region labelled A in Figure 2. The thalamic input to the dorsolateral region, while retaining its primitive connections with the distal processes of the apical dendrites, also projected to the cellular layers in the neocortical transformation. This new thalamic input was topographically organized and is the basis of the spatially ordered maps of vision, somesthesia and audition in the neocortex.

Acknowledgements

The ideas expressed in this paper will appear in a more extended form as a book entitled *Evolution of Neocortex* to be published by MIT Press. The work was supported by the Hixon Professorship of Psychobiology at the California Institute of Technology.

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