Evolution of Nervous Systems and Brains

2

Gerhard Roth and Ursula Dicke

The modern theory of biological evolution, as established by Charles Darwin and Alfred Russel Wallace in the middle of the nineteenth century, is based on three interrelated facts: (i) **phylogeny** – the common history of organisms on earth stretching back over 3.5 billion years, (ii) **evolution** in a narrow sense – modifications of organisms during phylogeny and underlying mechanisms, and (iii) **speciation** – the process by which new species arise during phylogeny. Regarding the phylogeny, it is now commonly accepted that all organisms on Earth are derived from a common ancestor or an ancestral gene pool, while controversies have remained since the time of Darwin and Wallace about the major mechanisms underlying the observed modifications during phylogeny (cf. [1]).

The prevalent view of **neodarwinism** (or better "new" or "modern evolutionary synthesis") is characterized by the assumption that evolutionary changes are caused by a combination of two major processes, (i) heritable variation of individual genomes within a population by mutation and recombination, and (ii) natural selection, i.e., selective environmental or genomic forces leading to better adaptation of those bearing the mutation and as a consequence to their greater differential reproductive success. The **modern synthesis** holds that evolutionary changes are gradual in the sense that larger, macro-evolutionary, changes are the sum of smaller, micro-evolutionary, changes. Other experts argue that such a gradualistic view of evolution (including "sexual selection" and "genetic

drift") is incomplete; they point to a number of other and perhaps equally important mechanisms such as (i) neutral gene evolution without natural selection, (ii) mass extinctions wiping out up to 90 % of existing species (such as the Cambrian, Devonian, Permian, and Cretaceous-Tertiary mass extinctions) and (iii) genetic and epigenetic-developmental ("**evo**-**devo**") self-canalization of evolutionary processes [2]. It remains uncertain as to which of these possible processes principally drive the evolution of nervous systems and brains.

2.1 Reconstruction of the Evolution of Nervous Systems and Brains

In most cases, the reconstruction of the evolution of nervous systems and brains cannot be based on fossilized material, since their soft tissues decompose, but has to make use of the distribution of neural traits in extant species. This is usually done by means of the phylogenetic or cladistic method as originally developed by the German entomologist Willi Hennig [3]. This method is based on whether a given character (or trait) represents an ancestral, *plesiomorphic*, or a derived, *apomorphic* state. The result of such an analysis is a "tree" called *cladogram* reflecting shared derived characters called *synapomorphies* or *homologies*. Characters used for the construction of a *cladogram* can be of any nature, but mostly are anatomical or biochemical. The standard criterion between competing cladograms is the **principle of parsimony** stating that the most likely evolutionary hypothesis is that minimizing the number of independent (*convergent* or *homoplastic*) steps of modification of the character under consideration. If different species of animals

G. Roth (✉) • U. Dicke
Brain Research Institute, University of Bremen,
28334 Bremen, Germany
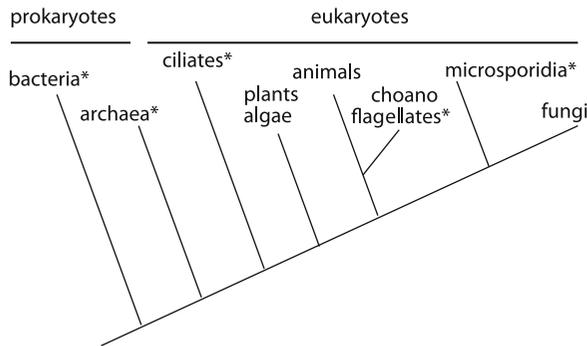e-mail: gerhard.roth@uni-bremen.de; dicke@uni-bremen.de

Fig. 2.1 **"Tree of life"**. Lifeforms are classified into prokaryotes (unicellular, without a cell nucleus) and eukaryotes (cells with a nucleus), the latter being either unicellular (*marked by* *, only some examples shown) or multicellular (fungi, plants, and animals). The phylogeny of these groups remains an open field of research

coincide in the formation of a given character in detail (e.g., the structure of the inner ear or the genetic sequence of a membrane channel), then it appears more likely that these species are related and the coincidence of characters is due to common ancestry, i.e., that they are *homologous*. However, there is increasing evidence that convergent-homoplastic evolution is much more common than previously believed, which weakens the principle of parsimony.

In the reconstruction of the evolution of nervous systems and brains, however, the primary goal is not the construction of new cladograms, but an answer to the question whether within a group (taxon) of animals the presence or absence of a given character, e.g., the six-layered isocortex as found in all mammals, represents an ancestral (plesiomorphic) or derived (apomorphic) state. This requires the availability of well-established cladograms, which are based on nonneural characters in order to avoid circular conclusions. However, such well-established cladograms do not always exist, and therefore one often has to operate with competitive cladograms.

Figure 2.1 illustrates the present knowledge about the major groups of organisms – the "tree of life". According to most recent evidence, the earth was formed about 4.5 billion years ago (bya). First organisms appeared about 3.5 bya as prokaryotic bacteria and archaea (these are organisms without a cell nucleus). Unicellular eukaryotes (which bear a cell nucleus) originated 2.7–1.6 bya, simple multicellular animals (sponges) about 1 bya, and coelenterates about 700 million years ago (mya). First deuterostomes and first arthropods appeared 570 mya, cephalopods as

well as first fishlike animals and proto-amphibians about 500 mya, insects about 400 mya, amphibians 360 mya, reptiles 300 mya, mammals 200 mya, and birds 150 mya. First human-like animals (australopithecines) appeared 4 mya, and modern humans (*Homo sapiens sapiens*) 200,000–150,000 years ago.

2.2   Organisms Without a Nervous System

Nervous systems and brains have a dual function, i.e., the maintenance of inner "vital" functions of the organism and the control of behavior of that organism within a given environment [4]. Unicellular organisms exert the same functions and exhibit remarkably complex behaviors, although they do not possess, by definition, a nervous system.

Bacteria sense nutritive substances (e.g., sugar) or toxins (e.g., heavy metal) in their environments through a large number of chemoreceptors as well as obstacles through mechanoreceptors [5]. This diverse information is integrated and, through a chain of complex chemical reactions, drives their flagella for movement. *Escherichia coli* has six flagella, each possessing a proton-driven motor, that are combined to one single superflagellum for forward propulsion ("run") as soon as receptors detect an increase in nutritive or a decrease in toxic substances. In the opposite case, the superflagellum disintegrates, and the single flagella move independently. As a consequence, *E. coli* starts "tumbling" and randomly changes its direction of movement until the receptors sense a new gradient, and a new "run" begins. The bacterium has a mini-memory, by which it can compare the incoming information with previous information, and this "knowledge" determines the behavior. Thus, even in these most primitive organisms we find the three basic components for adaptive control of behavior, i.e., a sensorium, a motorium and in between information storage and processing. Other bacteria or archaea like *Halobacterium* possess light-sensitive spots that make them swim toward sunlight.

Unicellular eukaryotes such as *Paramecium* or *Euglena*, despite their unicellular organization, exhibit a much more complex control of behavior than bacteria or archaea [6]. They possess either flagella composed of microtubules and attached to their front, which bend to perform a breakstroke, or cilia that cover the entire body and are able to exert coordinated movements, or pseudopodia. They gather information

about their environment through voltage-gated, hyper-polarizing potassium and depolarizing calcium ion channels, while voltage-gated sodium channels are absent and found only from planarians, possibly cnidarians onwards. The calcium and potassium channels are used, among others, for the release of forward and backward movement. Many protozoans respond to chemical, tactile, temperature and visual stimuli. *Euglena* and *Paramecium* and other unicellular eukaryotes possess light-sensitive organelles for phototaxis. It is debated whether they already possess an intracellular system for central movement coordination.

Figure 2.2 illustrates the phylogeny of the Metazoa, i.e., multicellular organisms, which are divided into Nonbilateria and Bilateria. Porifera (sponges, 8,000 species, all aquatic) are the simplest metazoans. They possess "independent effectors" or *myocytes*, which have sensori-motor functions and directly respond to stimuli, but are not electrically excitable [7]. Sponges can regulate the water stream through openings (ostia) inside their body by modifying the diameters of these ostia. The inner surface of the ostia is covered with choanocytes carrying one flagellum each, and their movement can drive the water through the ostium in a coordinated fashion. The presence of true nerve cells is debated, because there is no convincing evidence for electrical signal conduction.

2.3 Nervous Systems in Eumetazoans

Eumetazoans comprise all metazoans except the Porifera. The evolutionary origin of the first nerve cells among eumetazoans is still a matter of debate (cf. [7, 8]). One assumption is that sensory and nerve cells originated from neuromuscular cells, while other authors postulate an independent origin of sensory, nerve, and muscle cells from epithelial cells. The "paraneuron" concept proposes the evolution of nerve cells from secretory cells. Even unicellular eukaryotes, plants, and non-neuronal cells display many features of nerve cells such as membrane potential, transmitters and other neuroactive substances, membrane receptors, ion channels, many chemical processes relevant for "neuronal information processing", and even action potentials – all of which being more than 1 billion years old and thus older than nerve cells and nervous systems. One remarkable exception is the voltage-gated sodium channel, which
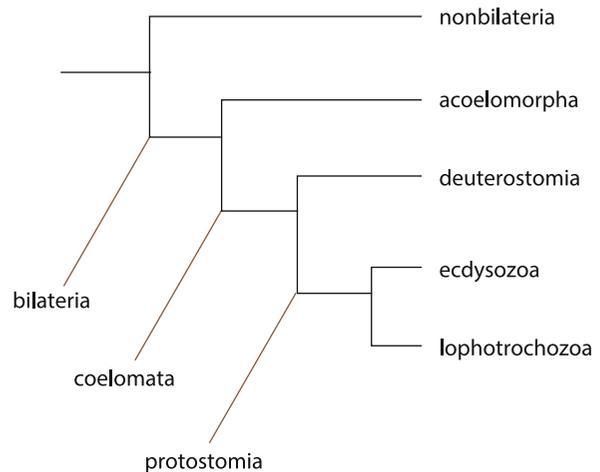

Fig. 2.2 **Phylogeny of metazoans,** i.e., multicellular animals. Metazoans comprise non-bilaterally organized animals (such as sponges and coelenterates) and bilaterally organized animals, which include those *without* a secondary body cavity (or coelom) – the Acoelomorpha, and those *with* a coelom – the Coelomata; for further explanation see text

is found first in planarians, perhaps already in cnidarians.

2.3.1 Coelenterata (Cnidaria, Ctenophora)

Coelenterates are nonbilaterian eumetazoans. Today they are considered two independent phyla, Cnidaria and Ctenophora (together about 11,000 species) and exhibit both the simplest types of nervous system (nerve nets) as well as relatively complex forms, i.e., radially symmetric nervous systems (Fig. 2.3). A central nervous system is absent [7]. The phylum Cnidaria comprises the sessile Anthozoa (sea anemones, corals), Scyphozoa (jellyfish), Cubozoa (box jellies), and Hydrozoa (hydras). Epidermal nerve nets are found in sessile hydrozoans like the freshwater polyp *Hydra*. There is a concentration (nerve rings) around the mouth and the peduncle of this animal. Complex sense organs are absent, but *Hydra* responds to mechanical, chemical, visual, and temperature stimuli. The free-swimming medusa forms of scyphozoans, in contrast, possess complex circular nervous systems inside the rim of the umbrella – the inner *subumbrellar* nerve ring contains large bipolar "swim motor neurons" for synchronous umbrella contraction, and the outer *exumbrellar* nerve ring consists of small multipolar sensory cells which are in contact with light-sensitive cells in mouth and tentacles. Both nerve rings are

Fig. 2.3 **The nervous system of the polyp *Hydra* (a) and radial section through the umbrella of a hydromedusa (b).** *ENR* exumbrellar nerve ring, *M* mesogloea, *RC* ring canal, *SNR* subumbrellar nerve ring, *SRM* subumbrellar ring muscle, *V* velum, *VRM* velar ring muscle (After Satterlie and Spencer [9] with permission)
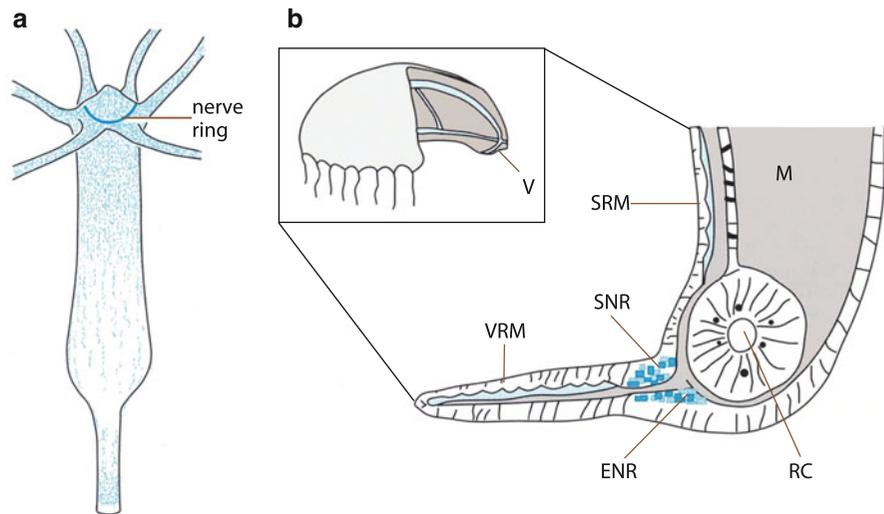
interconnected. Sensory organs are the ocelli (pigment spots, cup ocelli, or even "eyes" with biconvex lenses), statocystes (balance organs), and "rhopalia", i.e., complex clublike balance organs, often combined with photo- and chemoreceptors, which initiate the rhythmic contraction of the medusas. The nervous system of cnidarians is characterized by the dominance of electric synapses, although chemical synapses are likewise present. Chemical transmission is mostly exerted by a number of neuropeptides (e.g., FMRFamides and RFamides; cf. [10]), although there is evidence of cholingergic, serotonergic, dopaminergic, and glutamatergic transmissions in different cnidarians species.

2.3.2 Bilateria

Animals with bilateral symmetry ("Bilateria") comprise the three major groups of phyla, the Acoelomorpha, Protostomia, and Deuterostomia, the latter two together forming the "Coelomata", i.e., organisms with a secondary body cavity (see Fig. 2.2). However, the phylogeny of the Bilateria has not yet been firmly consolidated.

2.3.2.1 Acoelomorpha
Acoelomorpha include very small bilateral animals resembling flatworms and were previously assigned to the phylum Platyhelminthes (see below). They possess a diffuse subepidermal nerve net resembling that of *Hydra* and representing the simplest form of a bilateral nervous system. Since such diffuse subepidermal nerve

nets are likewise found in other flatworm-like organisms, it is not certain whether this type has evolved independently, e.g., via secondary simplification of more complex types [11] or represents the ancestral form of all bilateral nervous systems [12].

2.3.2.2 Protostomia
According to molecular phylogeny (cf. Fig. 2.2), protostome phyla are grouped into the Lophotrochozoa – animals carrying a lophophor (a complex feeding organ) or possessing a trochophora larva, and the Ecdysozoa, i.e., with ecdysis (see below). Many phyla of the lophotrochozoans include small and often sessile organisms such as the Bryozoa (also called Ectoprocta), the Brachiopoda, Echiura, Entoprocta, or Nemertini – all with simple to very simple (possibly simplified) nervous systems consisting of two or more nerve cords extending from a supraesophageal ganglion through the elongated body, which are connected by a number of commissures. In the following, only the larger phyla are described.

Lophotrochozoa
Platyhelminthes (flatworms; 25,000–30,000 species), comprise a number of species previously called "Turbellaria" (whereas other "turbellarians" are now included in the Acoela, which are not considered to belong to the Platyhelminthes), and the endoparasitic tapeworm groups Cestoda (tapeworms; 3,500 species) and Trematoda (flukes; about 20,000 species). The phylogeny of platyhelminths remains unresolved, however. "Turbellarian" platyhelminths may possess very
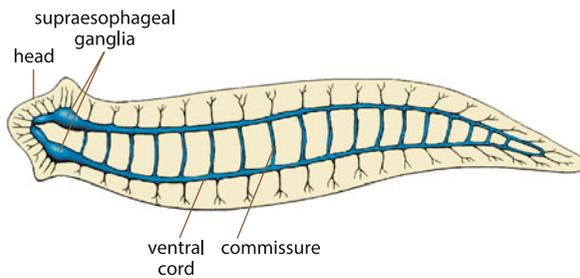
Fig. 2.4 **Nervous system and brain of a flatworm**. For further information see text

Fig. 2.5 **Eyes of "turbellarian" flatworms**. (**a**) Inverse pigment cup eye of a freshwater planarian (After Bullock and Horridge [8] and Paulus [13]). (**b**) Everse eye of a land planarian (After Bullock and Horridge [8] with permission)

simple nervous systems resembling the subepidermal diffuse nerve net found in the Acoela. In other forms, there is a supraesophageal ganglion giving rise to dorsal and ventral longitudinal cords connected by commissural tracts. The longitudinal cords can either consist entirely of fibers or of fibers forming regularly arranged ganglia (Fig. 2.4). The most complex nervous systems are found in predatory flatworms (planarians) such as *Notoplana* and *Stylochoplana* with cerebral ganglia consisting of five different "brain masses". Flatworms possess a variety of sense organs such as tactile or chemoreceptors on the head and all over the body, statocysts and inverse or everse pigment pit eyes containing several hundred photoreceptors (Fig. 2.5). Some of them are found as a pair of ocelli on the head, other terrestrial flatworms have more than 1,000 ocelli. Due to their endoparasitic life style, trematodes and cestodes have a simplified nervous system consisting of a simple "brain" and a varying number of longitudinal fiber tracts.

Annelida (segmented worms; about 18,000 species) are another large lophotrochozoan group. They are divided into Polychaeta (with hairs, chetae, and leglike parapodia) and Clitellata, the latter comprising oligochaetes (earthworms) and hirudineans (leeches), both without hairs and parapodia. Annelids possess a paired "ladder-type" central nervous system (Fig. 2.6). In its simplest state this structure consists of a cerebral or supraesophageal nerve ring or ganglion giving rise to paired ventral cords with a pair of ganglia per body segment connected by transverse connectives (anastomoses). In annelids, the cerebral ganglion has variously undergone an increase in complexity; in predatory polychaetes it has developed into a three-partite brain resembling the proto-, deuto-, and tritocerebrum of the insect brain (see below). Here, but also in some oli-
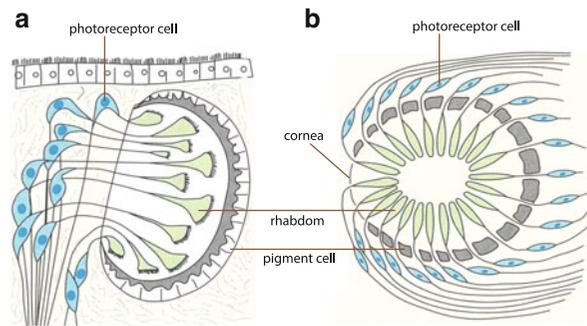
gochaetes, the first segments of the ventral nerve cord are often fused into a subesophageal ganglion. In the oligochaetes, we find a modest, and in hirudineans a massive simplification of this basic organization. Within the ventral nerve cord of most oligochaetes and some polychaetes there are giant fibers with very fast conduction velocity (three in oligochaetes) separated from the thinner fibers. Annelids possess a large variety of tactile and chemosensory organs, feelers or antennae, palps, and one ciliated "nuchal organ" possibly involved in light detection. Other light-sensitive organs range from very simple pigment spots and eye pits to compound eyes and lens eyes with accommodation mechanism in some predatory polychaetes, and have evolved independently of similar eye types in other animal groups (Fig. 2.7).

Molluska are the largest lophotrochozoan group (100,000 or more species). Their phylogenetic relationships are still unresolved. Besides several smaller groups, there are three large taxa, i.e., Gastropoda (snails and slugs, about 70,000 species), Bivalvia (clams, oysters, mussels, scallops; 10,000–20,000 species), and Cephalopoda (cuttlefish, squid, and octopods; about 800 species).

The molluskan nervous systems range from relatively simple (or simplified) forms resembling those found in acoelans to the most complex ones among invertebrates, in the cephalopods. The basic pattern is a *tetraneural* nervous system consisting of a cerebral ganglion, which gives rise to two dorsal pleurovisceral and two ventral pedal nerve cords. In the ancestral state, nerve cell bodies are not concentrated in ganglia, but are dispersed throughout the cords. The formation
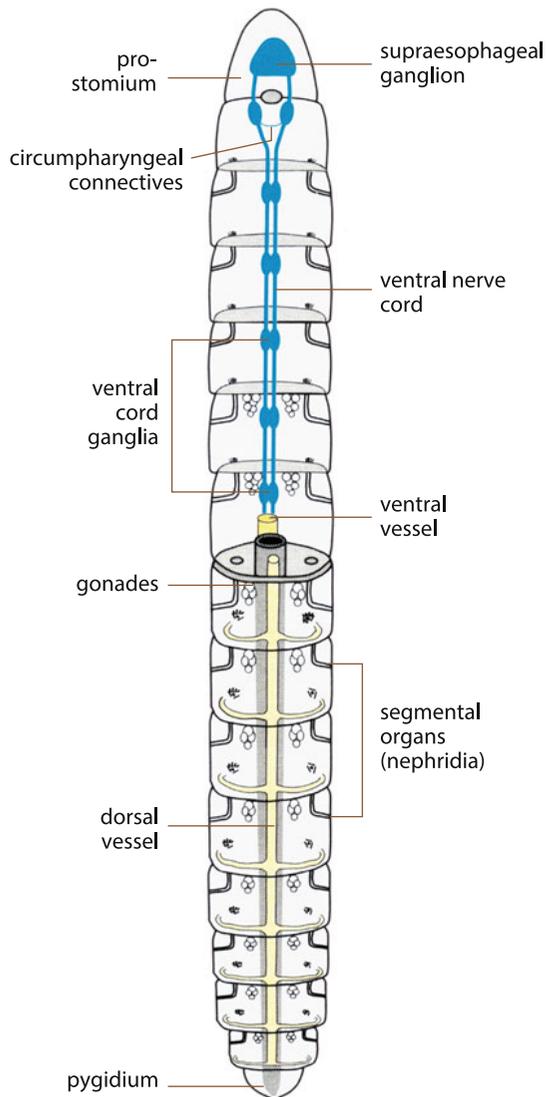
Fig. 2.6 Paired "ladder-type" central nervous system of annelids (After Hennig [14] with permission)

Fig. 2.7 Camera eye of the polychaete *Alciope* with lens accommodation mechanism. (**a**) Ventral view. (**b**) Cross section through the optical axis (After Bullock and Horridge [8] with permission)

of ganglia in mollusks is a derived state that occurred independently of the formation of ganglia in other forms such as annelids and arthropods.

Gastropoda

The nervous system of snails and slugs consists of four nerve cords – hence the term *tetraneural* nervous system – with maximally six pairs of ganglia and mostly one unpaired visceral ganglion (Fig. 2.8a). The nerve cords are mostly linked by commissures. The paired cerebral ganglia connected by a commissure are located around the esophagus and process information
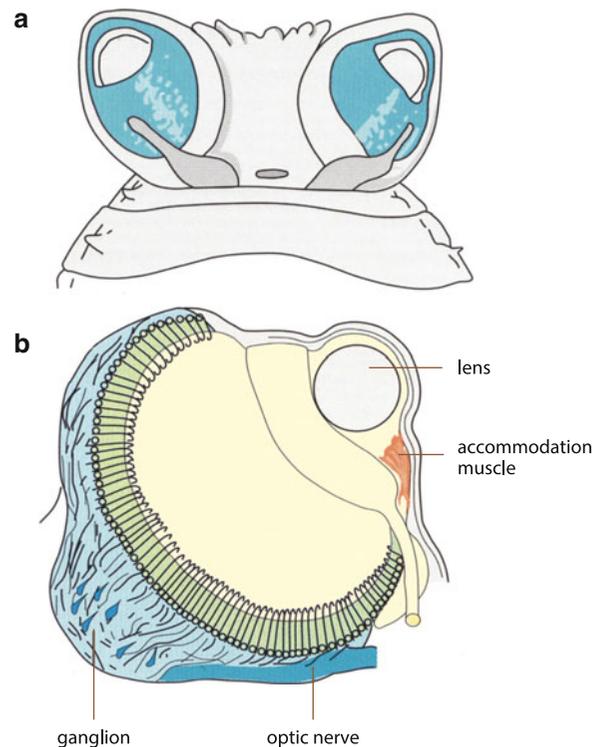
to and from the eyes, to statocysts, head tentacles, skin, and muscles of the lip, head, and sometimes penis region. One pair of buccal ganglia with a commissure is situated below the esophagus and innervates the pharynx, salivary glands, a nerve plexus of the esophagus and the stomach. One pair of pleural (i.e., lung membrane) ganglia without a commissure is connected by cords with the cerebral, buccal, and parietal-visceral ganglia. The pedal ganglia innervate feet muscles and skin. The cerebral, pleural, and pedal ganglia together form the "brain". The supra- and sub-intestinal ganglia innervate the gills, the "osphradium" (an olfactory organ) and parts of the mantle and skin; one pair of parietal ganglion (not present in all gastropods) innervates the lateral walls of the body. Finally, the unpaired visceral ganglion supplies the caudal region of the gut, anus, and neighboring regions of the skin and body wall, sexual organs, kidney, liver, and heart. It completes the "visceral loop", i.e., the chain of ganglia and cords from the pleural to the visceral ganglion.

A fusion of ganglia, mostly of the "visceral loop", is observed in many gastropods, e.g., in air-breathing landsnails. The most highly developed gastropod "brain" is found in *Helix pomatia* (the Roman or Burgundy snail). It consists of a protocerebrum with globuli (i.e., globe-like neuronal contact zones) and dense neuropils, a mesocerebrum, and a postcerebrum with pleural and pedal lobes. This organization is remarkably similar to that of other invertebrates with complex brains, but has presumably evolved independently.

Gastropods have chemoreceptive and mechanoreceptive sense organs distributed all over the body. Complex sense organs comprise statocysts, eyes ranging from widely open pit eyes (*Patella*), pinhole eyes (*Trochus*) to lense eyes (*Helix*), and chemosensitive osphradia in the mantle near the gills.

Some sea slugs have gained fame in modern neurobiology, e.g., the Californian "sea hare" *Aplysia californica*, which possesses some very large nerve cells that can be detected with the naked eye and are well-suited for studies of neuronal information processing and learning processes [15].

Bivalvia

Bivalves have a secondarily simplified nervous system with only three pairs of ganglia with an emphasis on the visceral ganglion, which is often fused with the parietal ganglia. In most species, the rostralmost ganglion is a fused cerebral, pleural, and buccal ganglion. Some bivalves, e.g., the scallop *Pecten*, have eyes on the rim of the mantle, often with a complex anatomy (e.g., a distal and proximal retina).

Cephalopoda

Cephalopods have highly developed nervous systems characterized by fusion of ganglia and subsequent development into lobes forming a complex brain around the esophagus. There are lobes that correspond to the cerebral, buccal, labial, pleural, and visceral ganglia of other mollusks, while innovative structures are the central optic-visual, olfactory, and peduncular ganglia as well as peripheral branchial and stellar ganglia (cf. [16, 17]).

The well-known *Nautilus* possesses a relatively simple brain without bulging supraesophageal lobes and with unfused subesophageal lobes, which probably represents the ancestral state of cephalopods. Members of the subclass Coleoidea comprising cuttlefish, squids,
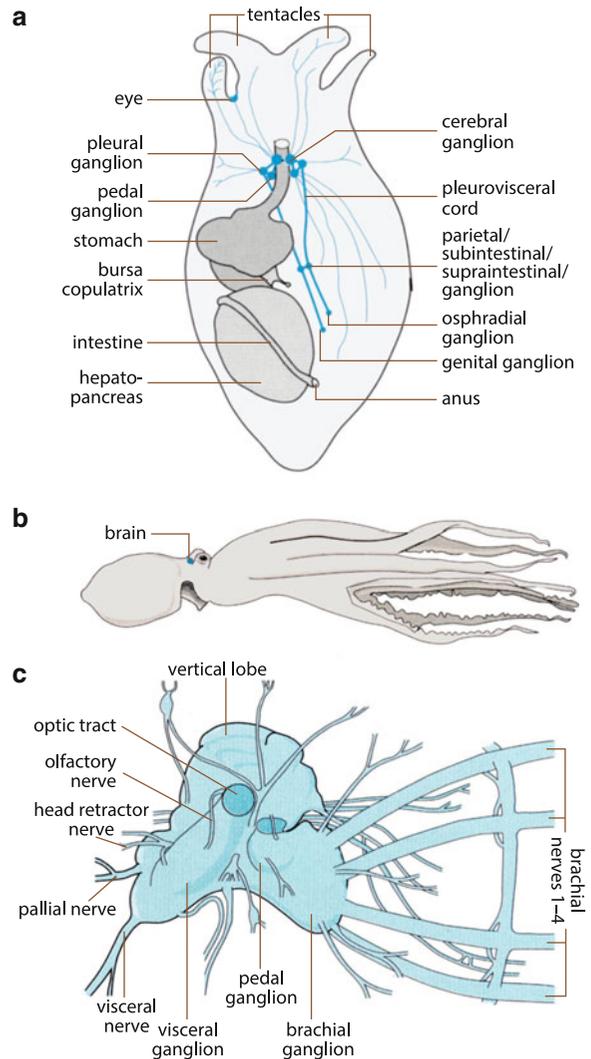
Fig. 2.8 **Central nervous system of mollusks**. (**a**) Nervous system of the sea slug *Aplysia*. (**b**) Site of the brain of *Octopus*, (**c**) *Octopus* brain and nerves (After Bullock and Horridge [8] with permission)

and octopods have much more complex brains. The most complex nervous system and brain of all invertebrates is that of the octopus (Fig. 2.8b, c). Its nervous system contains about 550 million neurons, 350 of which are located inside the eight arms, 120–180 million neurons in the giant optic lobes, and 42 million neurons in the brain. The latter encircles the esophagus and is composed of 38 lobes. The supraesophageal part is divided into 16 lobes and contains the mass of neurons. It has a ventral portion involved in the control of feeding and locomotion, and a dorsal portion exerting
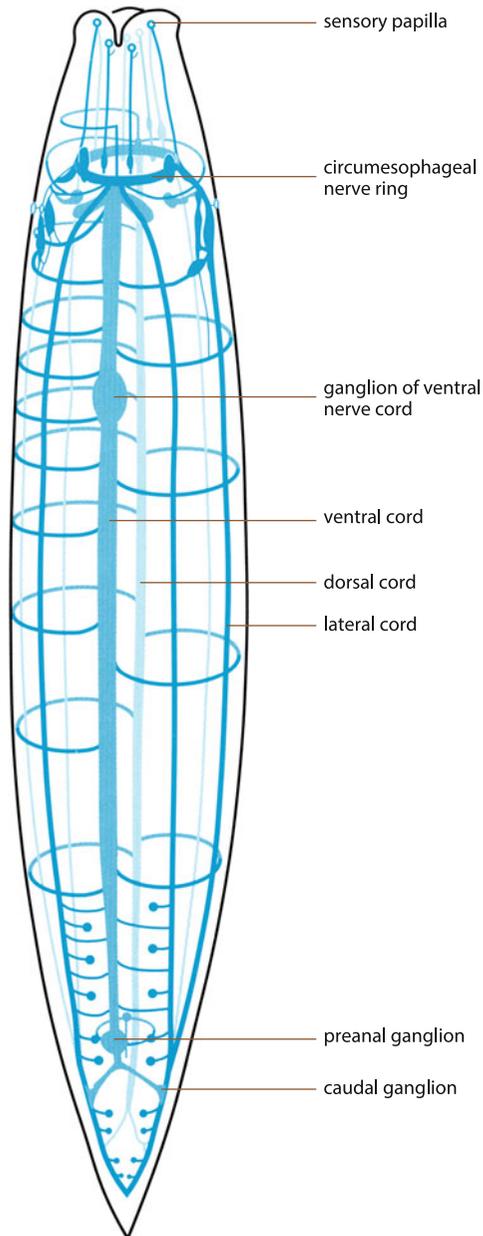
Fig. 2.9 **Central nervous system of the nematode** *Ascaris*, ventral view (After Bullock and Horridge [8] with permission)

astonishing learning and memory capacity of *Octopus* [18]. Likewise complex are the giant optic lobes exhibiting a laminar neuropil resembling the cortex of mammals. They process the visual information arriving from the large lens eyes. These eyes are capable of lens accommodation and pupil contraction achieved by muscles, and have a striking similarity to the vertebrate eye, although they are the product of convergent evolution.

Ecdysozoa

The Ecdysozoa comprise all invertebrate animals that shed their exoskeleton – a process called "ecdysis". According to present taxonomy they include eight phyla, the largest of them being the Nematoda and the Arthropoda. The smaller groups mostly have relatively simple or simplified brains and simple sense organs.

Nematoda

Nematodes (roundworms; about 28,000 species) are the most numerous multicellular animals on Earth. Probably due to their predominantly parasitic lifestyle, they have very simple nervous systems (Fig. 2.9) consisting of a nerve ring around the esophagus and a number of ganglia connected to this ring. Four to twelve ventral cords originate from the ring and are irregularly connected by half-sided commissures. Local ganglia and nerves are found in the caudal gut and anal region. Some nerves extend from the esophageal nerve ring to the sense organs in the "head" region such as sensory papillae and bristles. Other sense organs are chemoreceptive organs called "amphidia".

The tiny nematode *Caenorhabditis elegans* has become a model organism in molecular and developmental neurobiology by the work of the South African molecular neurobiologist Sydney Brenner and colleagues [19, 20], a reason being the fact that it has a very simple nervous system composed of exactly 302 neurons. The basic genetic features and the connectivity of this nervous system was completely mapped by those authors and subsequent studies explored the neural and molecular mechanisms responsible for a variety of behaviors shown by *C. elegans* [21].

Arthropoda

Arthropods are by far the largest (about 1.2 million species described, more than ten million estimated) and most diverse group of animals. They are divided into protoarthropods (onychophorans, possibly tardigrades) and euarthropods (chelicerates, crustaceans,

cognitive functions, mostly visual and tactile-chemosensory. The vertical lobe is considered the most complex part of the octopus brain. It is composed of five lobules and contains about 26 million neurons. The vertical lobe is closely connected to the subvertical lobe containing about 800,000 neurons, and the interaction of both lobes, processed by a spectacularly regular network of millions of fibers arranged in a rectangular fashion, is regarded as the neural basis of the

myriapods, and hexapods, the latter three taxa called "mandibulates"). Their taxonomy is not fully established.

Like annelids, arthropods have a ventral, regularly segmented, paired "ladder-type" nerve cord. Based on the new taxonomy of protostomes mentioned above, this organization either has evolved independently in the lophotrochozoans and ecdysozoans from an unsegmented "ur-bilaterian" nervous system or was ancestral and has been lost in many cases [11]. In all arthropods, the first ganglia have fused into a complex brain. In mandibulates there are three major brain divisions, i.e., a proto-, deuto-, and tritocerebrum. The protocerebrum is associated with the paired optic lobes, the deutocerebrum with the first and the tritocerebrum with the second pair of antennae. Mandibulates display a subesophageal ganglion having formed by fusion of the three first ventral ganglia. They supply the mouth region and mandibles, in crustaceans the first and second maxillae, in insects the maxillae, mandibles and labium. Caudal ganglia of the ventral cords exhibit a strong tendency to fuse and to form specialized abdominal structures [22].

Chelicerata

Extant Chelicerata (about 100,000 species) comprise the Arachnida (spiders, scorpions, mites, and others) and Xiphosura (horseshoe crabs). They all possess specialized feeding appendages called chelicerae (claw horns), while lacking antennae. The CNS of the chelicerates is characterized by the absence of a deutocerebrum because of lack of antennae; the tritocerebrum supplies the chelicerae. In xiphosurans, scorpions, and araneans (spiders) there is an increasing tendency towards fusion of ganglia during ontogeny. In many species of these groups the entire chain of ventral ganglia forms a compact mass around the mouth, in the araneans below the brain.

The brain (supraesophageal ganglion) of arachnids consists of a protocerebrum and tritocerebrum. In the anterior median part of the protocerebrum, corpora pedunculata ("mushroom bodies") are found, which – in contrast to insects – are exclusively visual neuropils associated with the secondary eyes. A central body is found in the posterodorsal part and is probably an integrative center for visual information from the main eyes. The homology of both the corpora pedunculata and the central body of arachnids with those of insects remains uncertain [22]. The tritocerebrum is the ganglion linked with the chelicerae and is often fused with the subesoph-
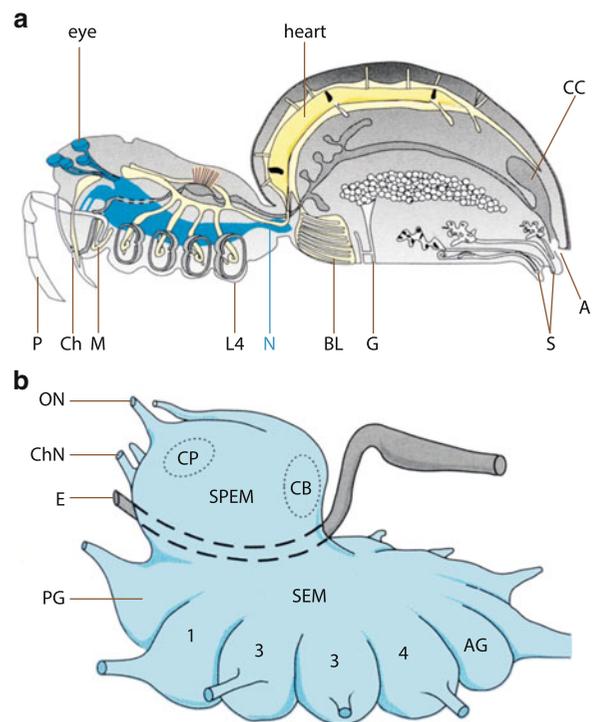

Fig. 2.10 **Central nervous system of arachnids**. (**a**) Site of the CNS (*blue*) inside the body of the house spider *Tegenaria*, side view (After Kästner [23]). (**b**) Closer view of the CNS. Abbreviations: *1–4* leg ganglia, *A* anus, *AG* abdominal ganglia, *BL* book lung, *CB* central body, *Ch* chelicerae, *CP* corpora pedunculata, *CC* cloacal chamber, *ChN* cheliceral nerve, *E* esophagus, *G* aperture of gonads, *L4* insertion of leg 4, *M* mouth, *N* nerve to abdomen, *ON* optic nerve, *P* pedipalp, *PG* pedipalp ganglion, *S* spinneret, *SPEM* supraesophageal mass, *SEM* subesophageal mass (After Foelix [24] with permission)

ageal mass supplying the legs. This mass is found below the brain. It consists of a highly variable number of fused ventral ganglia (16 in araneans) (Fig. 2.10).

Arachnids have a large variety of sense organs. There are vibration-sensitive slit-like lyriform organs involved in the detection of vibration and in proprioception and hair sensilla called "trichobothria" on the legs and lateral and dorsal parts of the body, which are involved in the detection of airborne vibration and air currents. Species differ in number of main and secondary eyes. The main eyes are considered homologous to the ocelli, and the secondary eyes to the compound eyes of insects.

Crustacea

Crustaceans (crabs, lobsters, crayfish, shrimp, krill, and barnacles; totaling >50,000 species) with the largest group Malacostraca (crabs, lobsters, crayfish) have
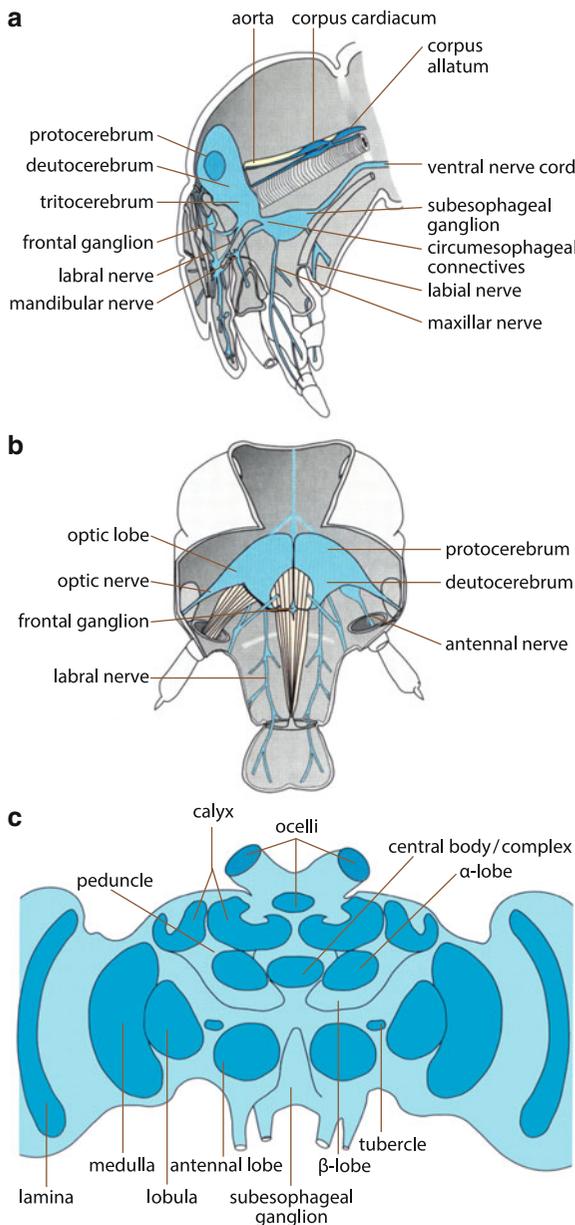
Fig. 2.11 **Insect brain**. (**a**) Lateral view and (**b**) ventral view of the brain and nerves in the scorpionfly *Panorpa* (After Bullock and Horridge [8]). (**c**) Schematic of the brain of a honey bee (After Mobbs [25] with permission)

a typical paired "ladder-type" nerve cord as the ancestral form. The brain (supraesophageal ganglion) is linked via two connectives with the ventral nerve cords. The protocerebrum consists of two lateral optic lobes and the median protocerebrum containing the anterior and posterior optic neuropils, the protocere-

bral bridge, and the central body. Neuropils of the optic lobes are highly variable. In decapod crustaceans (e.g., crabs), there are additional visual neuropils within the optic lobes, i.e., a terminal medulla and the so-called hemiellipsoid bodies, which some authors conceive to be homologous to the insect mushroom bodies (see below). Both include a varying number of complex neuropils; most of them contain glomeruli. The hemiellipsoid bodies and some of the other neuropils have connections with the accessory and olfactory lobes of the deutocerebrum. The deutocerebrum contains the medial and lateral neuropils receiving vestibular and mechanosensory input from the first antennae, the olfactory and parolfactory lobes (the latter with unknown input), and the lateral glomeruli. The tritocerebrum receives information from the second antennae and sends motor nerves to them. There are strong differences in the degree of fusion of ventral cord ganglia. A subesophageal ganglion controlling mouth appendages is found in many malacostracans, and the fusion of ganglia is maximal in crabs.

Crustaceans have a large number of sense organs. These comprise proprioceptive mechanoreceptors of leg joints, the chordotonal organs. The surface including distal limbs and antennae is covered with mechano- and chemoreceptors possessing sensilla or setae. Only malacostracans have vestibular organs. An unpaired nauplius eye, frontal simple eyes and compound eyes are found, the latter are located either directly on the head or on eyes elevated on movable stalks. The compound eyes can consist of a few or several 1,000 ommatidia.

Insecta (Hexapoda)

Insects are the largest group of arthropods, with an estimated 6–10 million species, most of which are terrestrial (as opposed to crustaceans). The nervous system of insects consists of a brain (supraesophageal ganglion) and ventral nerve cords (Fig. 2.11). The brain, formed by fusion of the first three ganglia, consists of a large protocerebrum, a smaller deutocerebrum, and a very small tritocerebrum. Fiber tracts connect the brain with the subesophageal ganglion, constituted by fusion of the first three ventral cord ganglia. The protocerebrum consists of two hemispheres, which are continuous with the lateral optic lobes receiving input from the compound eyes. Terminal fields of the nerves from the ocelli are found in the posterior median protocerebrum. The central complex

and the *corpora pedunculata* or "mushroom bodies" (MB), are located in the median protocerebrum (see below). The MB receive olfactory input from the antennae via the antennal lobes situated in the deutocerebrum and the antennocerebral tract (ACT). In hymenopterans (bees, wasps, ants) the MB also receive visual projections from the optic lobes, which terminate in the calyces of the MB. The optic tubercle is also found in the median protocerebrum which receives visual input from the optic lobes. These structures are connected with the ventral cords via descending tracts. The smaller deutocerebrum is connected with the protocerebrum by a supraesophageal commissure. Mechanoreceptive fibers terminate in its dorsal lobe. Here, the antennal lobe is found as terminal field of olfactory afferents from the antennae. Projection neurons of the antennal lobe send axons to the MB and to the protocerebral lobe of the protocerebrum via ACT. The deutocerebrum gives rise to the sensory and motor antennal nerves. The small tritocerebrum is related to taste perception and origin of the frontal connectives and the labral nerves.

The chain of ventral cord ganglia consists of subesophageal, thoracic, and abdominal ganglia. The first innervates the mandibles, maxillae, and labium as well as the neck musculature. It is also involved in the innervations of the salivary glands, the corpora allata (endocrine glands producing the juvenile hormone), and the frontal ganglion and is considered a higher motor center for the initiation and control of behavior. Most insects have three thoracic ganglia: a pro-, meso-, and metathoracic ganglion supplying legs and wings, if present, with sensory and motor nerves. Abdominal ganglia (11 in the embryonic stage) are reduced and fused during development.

The visual system of insects comprises the retina of the compound eye and three optic neuropils, the lamina, medulla, and lobula complex, which in flies and butterflies is divided into a lobula and lobula plate. In addition to the compound eyes, insects have dorsal eyes, so-called ocelli, which are simple lens eyes and thought to exert steering functions during walking and flight.

Antennae bear mechanosensitive, olfactory, hygroreceptive, and temperature-sensitive receptors. The neuropil of the antennal lobe in the deutocerebrum contains a species-specific number of glomeruli, in which sensory afferents and interneurons make contacts. Macroglomeruli are found in some male insects related to sexual pheromone processing.

The MBs in hymenopterans are composed of one calyx or two calyces (a medial and a lateral one) and a peduncle consisting of two lobes, alpha and beta. The somata of neurons ("Kenyon cells", bees having around 300,000) together with their axons ("Kenyon fibers") form the peduncle; the neuronal somata are located in the outer rim of the calyx. The Kenyon fibers split up – one collateral enters the α, and another the β lobe. In the honeybee, the calyces exhibit three vertically arranged regions, the lip, collar, and basal ring region. Afferents from the antennal lobe terminate in the lip region, afferents from the medulla and lobula of the optic neuropils terminate in the collar region, and the basal ring region receives collaterals from both afferents as well as from the subesophageal ganglion. The α and β lobes send fibers to the median protocerebrum between the two MBs, the protocerebral lobe lateral to the MB, the contralateral MB, the optic tubercle and back to their own calyces. In hymenopterans, the MB represents a highly complex multimodal center that forms the neural basis of processing and integrating olfactory/visual and mechanosensory information and enables learning (mostly olfactory and visual), complex cognitive functions, and complex behavior such as navigation [26]. Their output has sensory, movement-related, and sensorimotor functions. MBs differ substantially across species. For example, *Drosophila* only has a single cup, and spatially segregated α, β, and λ lobes.

The central complex of insects consists of four neuropils, i.e., the protocerebral bridge, an upper division (in *Drosophila* called fan-shaped body), a lower division (in *Drosophila* called ellipsoid body), and the paired nodules. It receives strong visual as well as mechanosensory input, but only weak input from the MB. Their precise function is still unclear, but the central complex has to do with premotor integration, orientation, and control of complex locomotion and path integration.

The homology of the MB and the central bodies (CB) or central complexes in arthropods is debated. The CB of insects and crustaceans are probably homologous, whereas homology with CB of chelicerates is controversial. The same holds for the MB in insects and crustaceans (here called hemiellipsoid body), on the one hand, and of chelicerates, on the other, partly because in the latter, the MB receive only visual input. Some authors place the MB of chelicerates closer to those of onychophorans [27]. Accordingly, the MB of
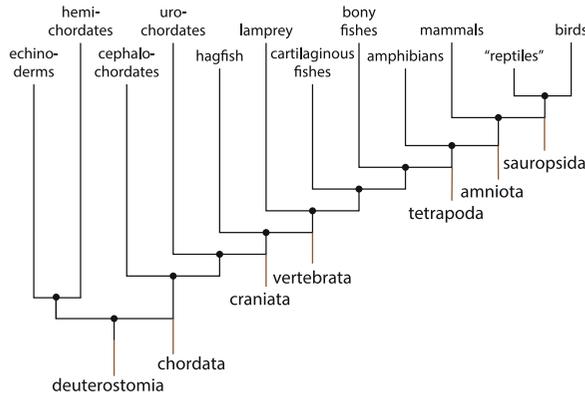
Fig. 2.12 Phylogeny of deuterostomes

ventral nerve cord interpreted by some authors to be homologous to the spinal cord of chordates, while others consider it a result of independent evolution.

Chordata

The phylum Chordata consists of the Cephalochordata (lancelets), Urochordata (tunicates), and Craniata (cf. Fig. 2.12). They all possess, at least at some point of their life, a chorda dorsalis or notochord, i.e., a flexible cartilaginous rod, and a hollow dorsal nerve or "spinal" cord.

Cephalochordata and Urochordata

Cephalochordates (21 species, e.g., the lancelet *Branchiostoma*, previously called *Amphioxus*) possess a neural plate, but no neural crest or placodes and, as a consequence, no head. Recent studies based on neural gene expression patterns [28] reveal that the neural tube and its rostral "cerebral vesicle" are homologous with most parts of the vertebrate CNS, i.e., a spinal cord, a rhombencephalon, mesencephalon, and diencephalon and perhaps parts of a telencephalon, which is connected with the unpaired frontal eye. Urochordates (2,200 species) are sessile animals having a free-swimming larva and a very primitive nervous system, probably as a consequence of secondary simplification related to their sessile life style.

Craniata/Vertebrata

The group Craniata (i.e., animals with a skull) comprises the Myxinoidea and all members of the subphylum Vertebrata including the group Petromyzontida (lampreys) (cf. Fig. 2.12). Myxinoids and petromyzontids have no jaws and are, therefore, often called Agnatha, i.e., jawless fishes.

Myxinoids (hagfishes; about 60 species) are eel-like exoparasites with a well-developed olfactory and mechanosensory system – no lateral-line system as in all other aquatic vertebrates – and have degenerated eyes.

Vertebrata

As shown in Fig. 2.12, the subphylum Vertebrata comprises the classes Petromyzontida (about 50 species), Chondrichthyes (cartilaginous fishes, i.e., sharks, rays, skates and chimaeras, about 1,100 species), Osteichthyes (bony fishes, i.e., actinopterygian, brachiopterygian, and sarcopterygian fishes, the latter comprising lungfishes and crossopterygians; together more than 30,000 species), Amphibia (frogs,

onychophorans and chelicerates would have evolved independently of those of the mandibulates or underwent substantial functional and structural changes in their ancestral organization.

2.3.2.3 Deuterostomia

As illustrated in Fig. 2.12, the superphylum Deuterostomia, i.e., animals with a "secondary mouth", comprise the phyla Echinodermata, Xenoturbellaria (not shown), Hemichordata, and Chordata. The split between protostomes and deuterostomes has happened in Precambrian time about 560 mya.

Echinodermata

The Echinodermata (starfish, sea urchins, sand dollars, brittle stars, sea cucumbers, and feather stars, together about 6,300 species) are radially symmetric (pentaradial) animals at the adult stage. The radial symmetry of body and nervous system appears to be secondary, since echinoderms most probably derive from bilaterally symmetric ancestors, as is reflected by their bilateral larva. The nervous system is composed of a sensory ectoneural nerve ring of ectodermal origin surrounding the mouth, and a motor hyponeural system of mesodermal origin, from which radial nerves enter the arms and the rest of the body coordinating the movement of the animal. The connection between the two systems is unclear.

Hemichordata

Hemichordates (with the classes Enteropneusta and Pterobranchia; 100 species) are wormlike or sessile marine animals with a primitive or secondarily simplified nervous system consisting of a dorsal and

salamanders, caecilians, about 6,000 species), "Reptilia" (chelonians, i.e., turtles; rhynchocephalians, i.e., the tuatara; squamates, i.e., lizards and snakes; and crocodilians – together about 9,500 species), Aves (birds, about 10,000 species), and Mammalia (about 5,700 species). The former class "Reptilia" is now considered a paraphyletic taxon, i.e., one without a common ancestor, because crocodilians (and the extinct dinosaurs) are more closely related to birds than to other "reptiles". The representatives of the former class "Reptilia" and birds together form the superclass Sauropsida.

The class Mammalia comprises the three subclasses Prototheria (egg-laying mammals, with the single order Monotremata, 5 species), Metatheria or Marsupialia (i.e., "pouched" mammals, about 340 species), and Eutheria or Placentalia (i.e., mammals with a placenta, 5,300 species). According to recent taxonomy, the latter comprises the four supraorders Afrotheria (containing elephants, manatees, and species previously included in the now obsolete group "insectivores"), Xenarthra (anteaters, armadillos, sloths), Euarchontoglires (e.g., primates, rodents, hares), and Laurasiatheria (including bats, carnivores, ungulates, cetaceans, and certain species previously referred to "insectivores").

The CNS of craniates reveals a highly uniform organization [29, 30] (Figs. 2.13 and 2.14a–j). In its hypothetical ancestral form, it exhibits the "standard" organization into the three: prosencephalon, mesencephalon, and rhombencephalon. Whether such a tripartite organization, occurring in lophotrochozoans as well as ecdysozoans, is due to "deep homology" found in all bilaterians [11] or to convergent evolution, is debated. All extant craniates have brains consisting of a rhombencephalon composed of a myelencephalon or medulla oblongata, and a metencephalon including a cerebellum, a mesencephalon (midbrain) including an isthmic region, and a prosencephalon composed of a diencephalon (or "primary prosencephalon") and a telencephalon (or "secondary prosencephalon" – endbrain). Medulla oblongata and mesencephalon together form the "brainstem". It is now generally accepted that most parts of the brain like the spinal cord have a *segmental organization* (Fig. 2.15). The rhombencephalon consists of rhombomeres R1–7, the mesencephalon is composed of an isthmic neuromer and a mesencephalic neuromer proper, the diencephalon (as "primary prosencephalon") and at least ventral parts of the
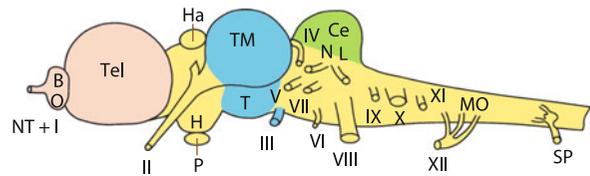

Fig. 2.13 **Basic organization of the vertebrate brain**. *BO* olfactory bulb, *Ce* cerebellum, *H* hypothalamus, *Ha* habenula, *MO* medulla oblongata, *NL* lateral nerves, *NT* terminal nerve, *P* hypophysis/pituitary, *SP* first spinal nerve, *T* tegmentum, *Tel* telencephalon, *TM* tectum mesencephali, *I–XII* cranial nerves

telencephalon (as "secondary prosencephalon") are segmented into six prosomeres P1–6. The exact segmentation of the telencephalon dorsal and rostral to P6 into pallial and subpallial regions has yet to be determined.

The *medulla spinalis* consists of an inner gray substance around the central canal consisting mostly of nerve cells covered by white substance containing dendrites and ascending and descending nerve fibers. The gray substance is divided into a dorsal somatosensory and viscerosensory region and a ventral visceromotor and somatomotor region. Nerve cells innervate the various parts of the body via spinal nerves in a segmental fashion.

The *medulla oblongata* reveals the same dorsoventral organization as the medulla spinalis and contains, in all vertebrates, from dorsal to ventral: somatosensory, viscerosensory, visceromotor, and sensorimotor areas and nuclei of the cranial nerves V to X. Tetrapod vertebrates (amphibians, "reptiles", birds, and mammals) also have the additional cranial nerves XI (*N. accessorius*) and XII (*N. hypoglossus*). The dorsal sensory roots of the cranial nerves include ganglia containing the somata of sensory neurons. The regions of sensory nuclei may undergo strong enlargement and complication, as, for instance, in goldfish with the gustatory vagal lobe and its highly evolved gustatory system. A mechano- and electroreceptive lateral-line system associated with cranial nerves is present in all vertebrates and was lost in some terrestrial amphibians and in all amniotes, i.e., in "reptiles", birds, and mammals.

The *reticular formation system* is found inside the medulla oblongata, the pons (only in mammals, though birds have evolved a somewhat similar structure independently), and in the tegmental midbrain. It is relatively uniform among vertebrates and contains
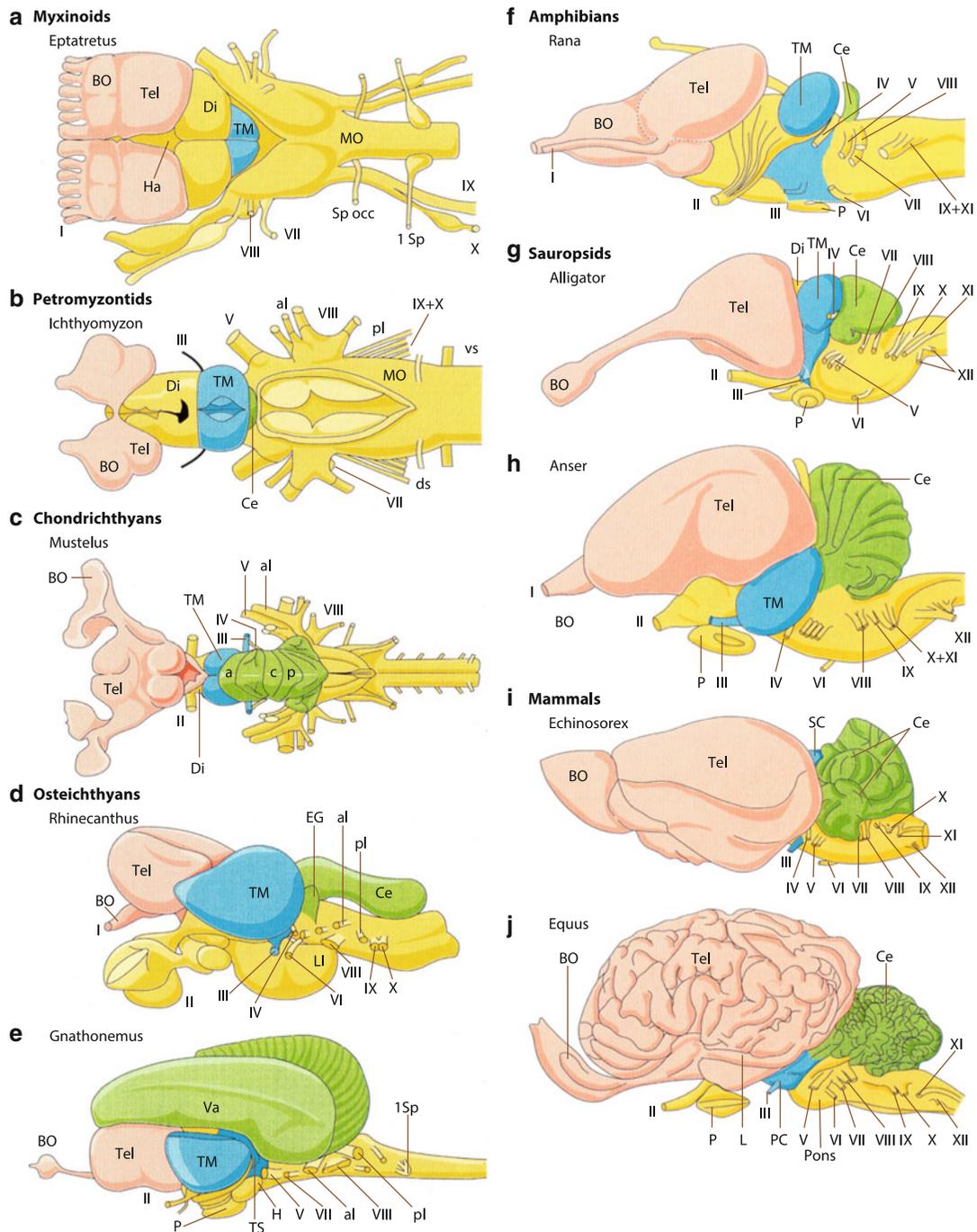
Fig. 2.14 **Brains of representatives of major groups of craniates**. (**a**) Hagfish, dorsal view (After Northcutt [31]). (**b**) Lamprey, dorsal view (After Northcutt [31]). (**c**) Common smooth-hound, dorsal view (After Northcutt [32]). (**d**) Trigger fish, lateral view. (**e**) Elephantnose, lateral view. (**f**) Frog, lateral view. (**g**) Alligator, lateral view. (**h**) Goose, lateral view. (**i**) Moon rat. (**j**) Horse, (**d–j**) after Romer and Parson [33]). For abbreviations see Fig. 2.13; further abbreviations: *a* anterior cerebellar lobe, *al* anterior lateral nerve, *c* central cerebellar lobe, *Di* diencephalon, *ds* dorsal spinal nerve, *EG* eminentia granularis, *H* habenula, *P* pituitary, *LI* inferior lobe, *p* posterior cerebellar lobe, *pl* posterior lateral nerve, *SC* superior culliculus, *Sp occ* spino-occipital nerve, *1Sp* first spinal nerve, *TS* torus semicircularis, *Va* valvula cerebella, *vs* ventral spinal nerve

important neuromodulator-producing centers such as the noradrenergic *locus coeruleus* and the serotonergic *raphe* nuclei. The reticular formation controls centers for breathing and cardiovascular activity and gives rise to an ascending activation system for vigilance, awareness, and consciousness. A *pons* ("bridge") is found only in mammals and is situated in the rostral medulla oblongata and caudal tegmentum. It contains relay nuclei of fiber bundles that connect the cerebral cortex and the cerebellum. However, similar pathways and nuclei are likewise found in birds, but most likely developed independently.

The *cerebellum* is a formation of the dorsal metencephalon and present in all vertebrates, but absent in myxinoids, perhaps due to secondary loss. In all vertebrates except petromyzontids, it exhibits a uniform three-layered organization, i.e., a deep small-celled granular layer, a large-celled layer of Purkinje cells, and a peripheral molecular layer. The vestibulolateral lobes of the cerebellum processing primary vestibular and – if present – mechano- and electroreceptive lateral-line information are present in all vertebrates. A *corpus cerebelli* is found in cartilaginous and bony fishes and terrestrial vertebrates and has undergone hypertrophy in some groups of cartilaginous fishes, and is strongly reduced in size in amphibians. In some actinopterygian fishes, predominantly in electric fish, there is a strong enlargement of parts of the cerebellum, the *valvula* [34]. Mammals have novel lateral cerebellar structures, the *cerebellar hemispheres*, receiving telencephalo-pontine input. Besides vestibular, somatosensory, and sensorimotor functions, the cerebellum of mammals, and perhaps of birds, is likewise involved in "higher" cognitive functions such as thinking and action planning as well as language in humans.

The *mesencephalon* consists, from dorsal to ventral, of the: *tectum* (in mammals called "colliculi superiores"), the *torus semicircularis* (in mammals called "colliculi inferiores"), and the *tegmentum*. In all craniates, except mammals, the tectum is the major visual processing and integration center. In its ancestral state, it exhibits a laminar organization consisting of alternating cellular and fiber layers. The absence of such lamination in some vertebrates such as salamanders, caecilians, and South American and African lungfishes is a consequence of secondary simplification [35]. Besides visual input, other sensory information such as auditory and – if present – mechano- and electrosensory information originating in the torus semicircularis terminate in deeper layers of the tectum and
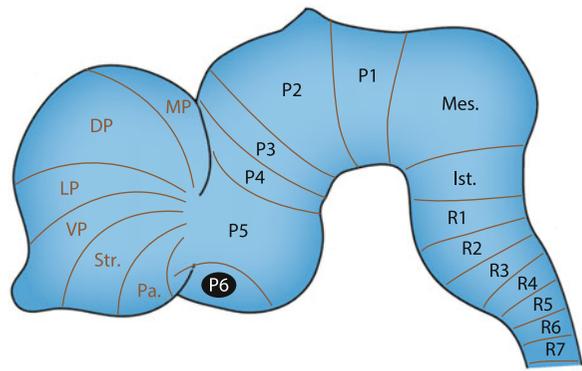

Fig. 2.15 **Segmental organization of the craniate brain**. *DP* dorsal pallium, *Ist.* isthmic neuromer, *LP* lateral pallium, *Mes.* mesencephalic mesomer, *MP* medial pallium, *P1–6* prosomeres, *Pa.* pallidum, *R1–7* rhombomeres, *Str.* striatum, *VP* ventral pallium (After Striedter [30] with permission)

contribute to a multimodal representation for orientation in space. Likewise, telencephalic efferents terminate in the tectum of cartilaginous and bony fishes and of terrestrial vertebrates. Main tectal efferents descend to the medulla oblongata/pons and medulla spinalis (tectobulbar and tectospinal tracts, respectively).

The *torus semicircularis* is, in its plesiomorphic state, the midbrain relay station for auditory, mechano-, and electrosensitive projections ascending to the diencephalon and telencephalon (cf. Fig. 2.16d). Like the tectum, it is characterized by a laminar organization, which is most spectacular in electric fish [29] (cf. Fig. 2.17).

The *tegmentum* is involved in (pre)motor functions and exhibits a number of specialties. One ancient component is the nucleus of the oculomotor nerve (cranial nerve III), which is absent in myxinoids, but present in all vertebrates. In the tegmentum, massive fiber tracts descending from the cortex to the pons, medulla oblongata, and medulla spinalis are found (corticopontine tracts and pyramidal tract). The tegmentum contains the dopaminergic *substantia nigra* exhibiting reciprocal connections with the telencephalic striatum, and the premotor *nucleus ruber*. The latter receives crossed efferents from the cerebellum and gives rise to crossed descending motor tracts to the spinal cord (rubrospinal tracts).

The *diencephalon* is divided from dorsal to ventral into the epithalamus, thalamus, and hypothalamus (Fig. 2.16c). The *epithalamus* contains the *habenular nuclei*, which are important parts of the limbic system and present in all craniates. They project, via the
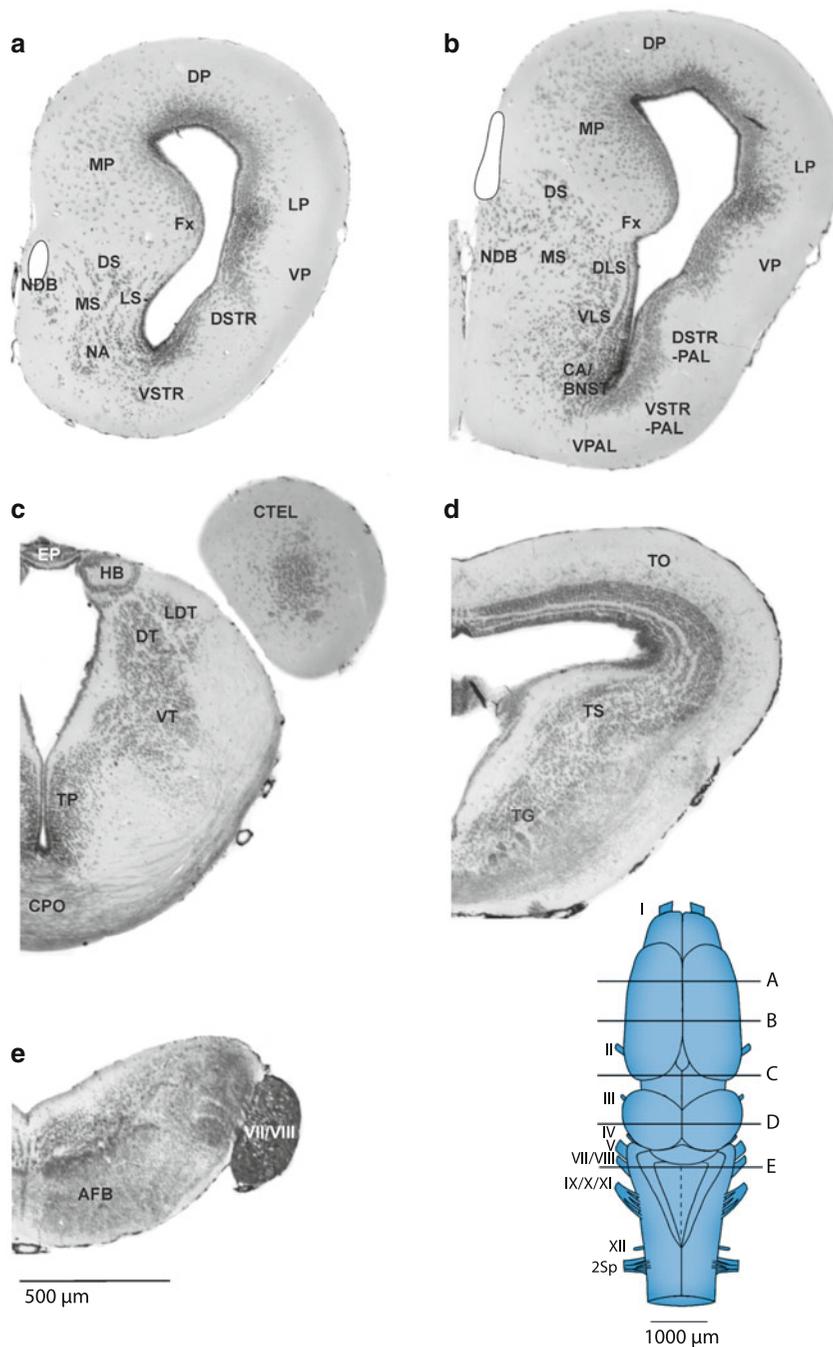
Fig. 2.16 Cross sections through the brain of the frog *Bombina orientalis*. Levels of cross sections (**a–e**) are indicated in dorsal view of the brain at *lower right*. (**a**) Rostral telencephalon at the level of the nucleus accumbens. (**b**) Central telencephalon at the level of dorsal and ventral striatum. (**c**) Diencephalon at the level of the habenula and postoptic commissure. (**d**) Midbrain with optic tectum and torus semicircularis. (**e**) Rostral medulla oblongata at the level of entrance of cranial nerve VII. Abbreviations: *AFB* descending fiber bundles, *CA-BNST* central amygdala-nucleus interstitialis of the stria terminalis, *CPO* commissura postoptica, *CTEL* caudal telencephalon, *DLS* dorsal lateral septum, *DS* dorsal septum, *DP* dorsal pallium, *DSTR* dorsal striatum, *DSTR-PAL* dorsal striatopallidum, *DT* dorsal thalamus, *EP* epiphysis/pineal organ, *Fx* fornix, *HB* habenula, *LP* lateral pallium, *LS* lateral septum, *LDT* lateral dorsal thalamus, *MP* medial pallium, *MS* medial septum, *NA* nucleus accumbens, *NDB* nucleus of diagonal band of Broca, *TG* tegmentum, *TO* optic tectum, *TP* tuberculum posterius, *TS* torus semicircularis, *VLS* ventral lateral septum, *VSTR* ventral striatum, *VSTR-PAL* ventral striatopallidum, *VP* ventral pallium, *VT* ventral thalamus, *VII/VII* 7th/8th cranial nerve, *2SP* 2nd spinal nerve

Fig. 2.17 **Anatomy of the torus semicircularis of the electric fish *Eigenmannia virescens*** exhibiting a spectacular laminar organization. (**a**) Afferents from different brain regions terminate in different layers of the torus. (**b**) Laminar organization of the torus in bodian staining. (**c**) Cytoarchitecture of the torus in golgi staining. Abbreviations: *Cb* cerebellum, *EL(P)/EL(T)* electrosensory P- and T-type afferents, *Vdesc* nucleus descendens of the trigeminal nerve, *Tec* tectum opticum, *Tl* torus longitudinalis, *Vb* vertical bundle (After Nieuwenhuys et al. [29], modified, with permission)
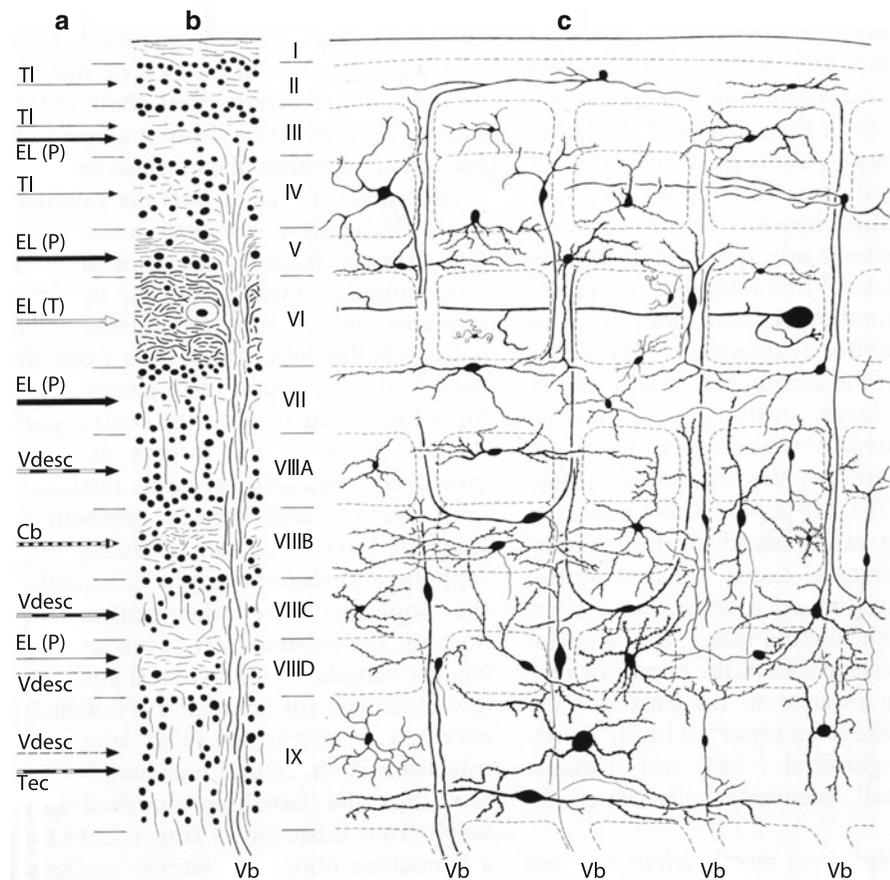
fasciculus retroflexus, to the midbrain tegmentum. In many craniates, the epithalamus carries the pineal organ or "epiphysis", a small endocrine gland releasing the hormone melatonin, which affects wake-sleep patterns and seasonal functions. The *thalamus* is composed of a dorsal and a ventral part and the posterior tuberculum. In all craniates, the *dorsal thalamus* receives visual, somatosensory, auditory, and gustatory information, either directly (e.g., from the eyes) or indirectly via brainstem relay centers, and sends them to telencephalic regions. Visual pathways terminate in the dorsal pallium of fishes, amphibians, "reptiles", and birds and in the occipital cortex of mammals. In "reptiles" and birds, auditory as well as visual and somatosensory pathways terminate in a special region of the lateral telencephalon called *dorsal ventricular ridge* (DVR) in "reptiles" and *mesonidopallium* in birds. The thalamus has undergone a strong enlargement in amniotes, particularly mammals and birds, and became parcellated into many nuclei related to sensory, cognitive, and motor as well as limbic functions. In mammals (Fig. 2.18), visual functions are relayed by

the corpus geniculatum laterale, auditory functions by the corpus geniculatum mediale, both projecting to the primary visual and auditory cortex, respectively. Ray-finned fishes have independently developed a projection from the posterior tuberculum of the diencephalon to the pallium. The *ventral thalamus* and subthalamus (zona incerta) of mammals projects to telencephalic parts of the basal ganglia, i.e., corpus striatum and globus pallidus, and to the hippocampus. The *hypothalamus* and its appendage, the *pituitary* (*hypophysis*), are the main hormone-based control centers for basal homeostatic functions. Cartilaginous and bony fishes exhibit a hypertrophy of the lateral hypothalamus (*lobus inferior hypothalami*), with unknown functions.

The evolution of the *telencephalon* in craniates is not fully understood. In all craniates, it receives olfactory information from the olfactory bulb as the only direct sensory input. Comparative neuroanatomists, therefore, previously believed that in its ancestral state the telencephalon had to be considered the "olfactory brain". Later it was found that in all craniates the

Fig. 2.18 Cross section through the human brain. (**a**) At the level of hypothalamus, amygdala, and striatopallidum. (**b**) At the level of hippocampus and thalamus. Numbers: *1* cerebral cortex; *2* nucleus caudatus, *3* putamen, *4* globus pallidus, *5* thalamus, *6* amygdala, *7* hippocampus; *8* hypothalamus, *9* insular cortex, *10* claustrum, *11* fornix, *12* nucleus ruber, *13* infundibulum of pituitary, *14* nucleus subthalamicus, *15* substantia nigra, *16* corpus callosum (After Nieuwenhuys et al. [36] with permission)
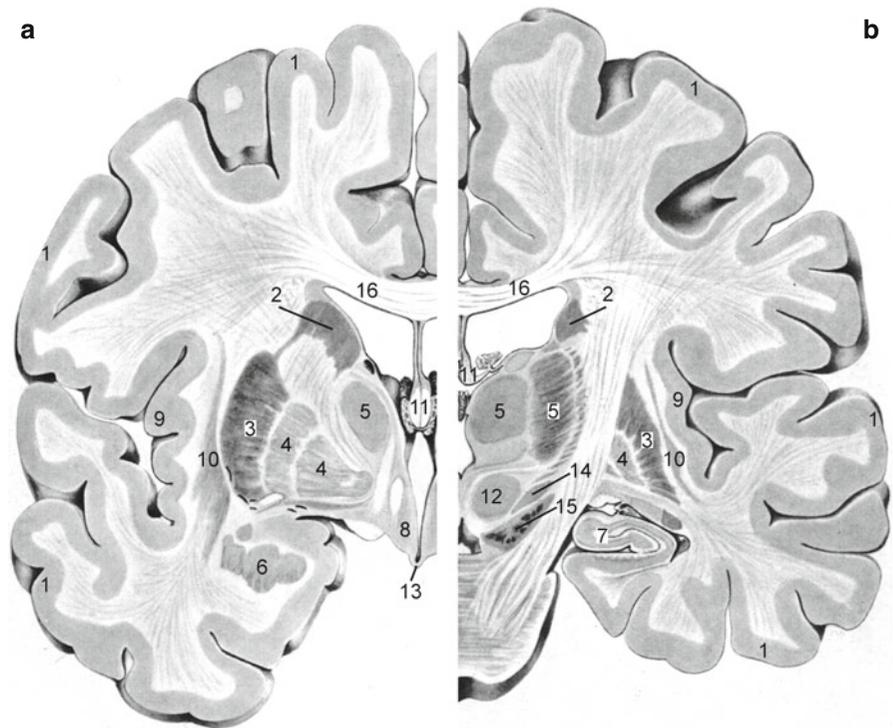
telencephalon also receives information from other senses, e.g., visual, auditory, and mechanosensory via pathways ascending from the diencephalon (see above), and the telencephalon was regarded "multimodal" in its ancestral state. Recent studies, however, revealed that in all craniates except birds and mammals these nonolfactory sensory afferents to the telencephalon are either multimodal or do not form topographic representations. This would imply that the development of topographic representations of thalamic sensory afferents to pallial/cortical regions has happened independently in birds and mammals and would again strengthen the "olfactory brain" interpretation.

The telencephalon of all craniates is composed of a pallium and a ventral subpallium ("pallium" means "mantle") surrounding the paired telencephalic ventricles, which in its ancestral form of tetrapods is clearly visible in the amphibian brain ([35] cf. Fig. 2.19). With the exception of petromyzontids, the pallium is divided into a medial, dorsal, lateral, and ventral pallium, and the subpallium into a septal and a striato-pallidal region, the latter including parts of the amygdala involved in limbic-autonomic functions (in mammals the "central amygdala"). In "reptiles", pallial divisions are called medial, dorsal, and lateral

cortex and dorsal ventricular ridge (see below). The medial pallium/cortex of amphibians and sauropsids corresponds to the hippocampal formation of mammals, the lateral pallium to the olfactory (in mammals "piriform") cortex, and the ventral pallium to the vomeronasal pallium.

The ontogeny of the telencephalon of actinopterygian (ray-finned) fishes deviates from that of other craniates [34]; Fig. 2.19. In the latter, the unpaired embryonic telencephalon extends laterally and forms two hemispheres through *evagination* resulting in an arrangement of a medial, dorsal, lateral, and ventral pallium, and a subpallium around the ventricles. In contrast, in actinopterygians two hemispheres are formed by *eversion* in such a way that parts of the brain which in the evagination type are found medially and dorsally, occupy a ventrolateral position. These differences in ontogeny contribute to the difficulty with homologizing parts of the telencephalon of actinopterygian fishes and other vertebrates.

In sauropsids, the lateral parts of the pallium have developed into a large structure, the *dorsal ventricular ridge*, DVR, which bulges in medial direction into the ventricles and for a long time was considered part of the corpus striatum as the major telencephalic
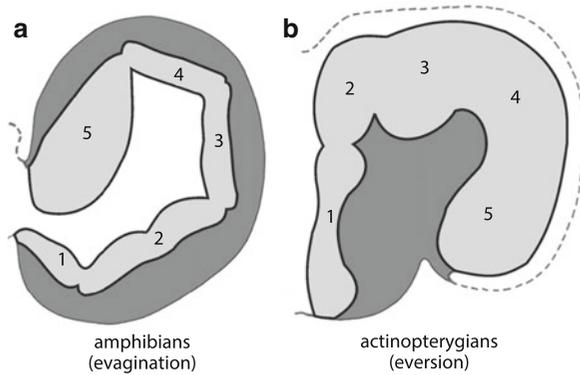
Fig. 2.19 **Differences in ontogenies of the telencephalon**. (**a**) Evaginated telencephalon as in most vertebrates (here amphibians). (**b**) Everted telencephalon as in actinopterygian bony fishes. *Numbers* indicate the major regions of the telencephalon: *1* ventromedial subpallium, *2* ventrolateral subpallium (striatopallidum), *3* lateral pallium, *4* dorsal pallium, *5* medial pallium. After Nieuwenhuys et al. [29], modified, with permission
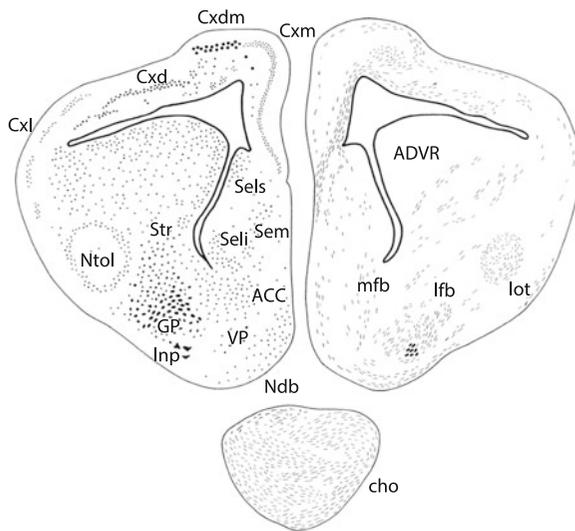

Fig. 2.20 **Cross section through the telencephalon of the lizard** *Tupinambis teguixin* at the level of the striatum. The anterior dorsal ventricular ridge (ADVR) bulges into the telencephalic ventricle. Abbreviations: *ACC* nucleus accumbens, *cho* chiasma opticum, *Cxd* cortex dorsalis, *Cxdm* cortex dorsomedialis, *Cxl* cortex lateralis, *Cxm* cortex medialis, *fx* fornix, *lfb* lateral forebrain bundle, *lot* lateral olfactory tract, *mfb* medial forebrain bundle, *Ndb* nucleus of the diagonal band of Broca, *Ntol* nucleus of the tuberculum olfactorium, *Seli* inferior lateral septum, *Sels* superior lateral septum, *Sem* medial septum, *Str* striatum, *VP* ventral pallidum (From Nieuwenhuys et al. [29], modified, with permission)

component of the basal ganglia (Fig. 2.20). Accordingly, parts of the DVR of birds were called e*ctostriatum*, *neostriatum*, and *hyperstriatum*. Today it is generally accepted that the DVR is not homologous to the striatum, but is of pallial origin [37].

However, as illustrated in Fig. 2.21, there is a debate whether the DVR and the mesonidopallium of birds are homologous to the lateral cortex or the claustrum of mammals and ventral pallium of amphibians [38, 39]. In the latter case, different parts of the dorsal telencephalon would give rise to centers involved in intelligence and other mental abilities (see below).

The dorsal pallium of myxinoids exhibits a five-layered structure, which has developed independently of other lamination patterns found in craniates (see below). The pallium of cartilaginous and actinopterygian fishes is unlaminated. The medial and dorsal pallium of lungfishes (dipnoans) displays some lamination, while the pallium of amphibians is generally unlaminated despite extensive cell migration in medial and dorsal parts [29]; cf. Fig. 2.18a, b. In the medial, dorsomedial, and dorsal cortex of "reptiles" there is a three- to four-fold lamination, which however, is discontinuous and not comparable in its cytoarchitecture to the laminated cortex of mammals (cf. Fig. 2.20). In birds, the dorsally situated hyperpallium is considered homologous to the visual, auditory, and somatosensory cortex of mammals, while the meso-/nidopallium of birds is considered to be homologous either to the lateral (temporal) isocortex or a derivative of the ventral pallium of amphibian-reptilian ancestors. In birds, both the hyperpallium and meso-/nidopallium are unlaminated (Fig. 2.22).

Mammals in general possess a six-layered cortex called "isocortex" (Fig. 2.23) and a 3- to 5-layered "allocortex" or limbic cortex. The evolution of the mammalian cortex is unclear, but its laminar organization appears to have evolved independently of the lamination occurring in the pallia of other craniates and probably evolved from a three-layered olfactory cortex. A common organizational principle of the mammalian cortex is the parcellation into functionally different (sensory, motor, integrative) areas. In small mammalian brains, the number of such areas is low, having about 10 primary sensory and motor areas without signs of integrative-associative areas; cf. [41]. The number of cortical areas increases with cortex volume in most mammals and all primates. Concurrently,
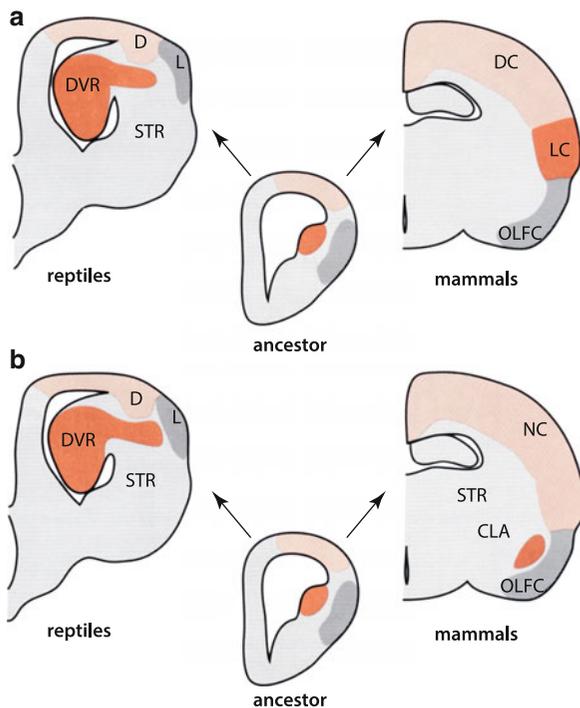
Fig. 2.21 Two hypotheses concerning the homology of the lateral mammalian cortex (LC) and the dorsal ventricular ridge (DVR) of "reptiles". (a) Hypothesis of "common origin" of the DVR and LC from the same embryonic material of the amniote ancestor. (b) Hypothesis of the de-novo formation of LC and DVR. For further information see text. Abbreviations: *CLA* claustrum, *D* dorsal cortex of reptiles, *L* lateral cortex of reptiles, *DC* dorsal cortex of mammals, *LC* lateral cortex of mammals, *NC* neocortex of mammals, *OLFC* olfactory cortex, *STR* striatum (From Striedter [30], modified, with permission)

the relative sizes of cortical areas are supposed to decrease. The human cortex is assumed to possess 150 areas and 60 connections per area resulting in 9,000 area-area connections [42].

The subpallium/subcortex of vertebrates consists of a large striatopallidum (*nucleus caudatus* and *putamen*, together forming the "corpus striatum", and *globus pallidus* in mammals; cf. Fig. 2.17) as the main component of the basal ganglia, a subcortical amygdalar complex, and a medially situated septal region. The amygdala of vertebrates consists of a portion exerting autonomic-limbic functions ("central amygdala") as well as olfactory and vomeronasal functions (cortical and medial amygdala of mammals, respectively). In addition, in mammals a basolateral amygdala has evolved, with strong reciprocal connections to the isocortex and limbic cortex
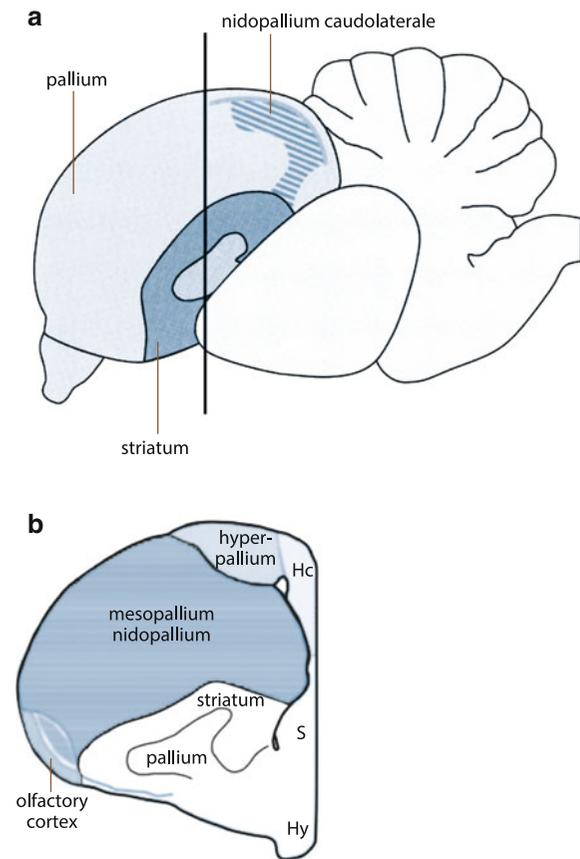

Fig. 2.22 Brain of a pigeon. (a) Lateral view. The telencephalon is composed of a pallium and a striatopallidum. A special pallial region is the nidopallium caudolaterale; (b) Cross section through the telencephalon at the level indicated in (a). Most of the pallium consists of the mesopallium and nidopallium. The hyperpallium is situated mediodorsally. Striatum and pallidum are located below the meso-/nidopallium. Abbreviations: *Hc* hippocampus, *S* septum, *Hy* hypothalamus. For further information see text ((a) After Gunturkun [43], modified, with permission. (b) After Reiner et al. [38], modified, with permission)

as well as afferents from the sensory nuclei of the thalamus.

2.4 Major Evolutionary Changes of the Vertebrate Brain

The basic organization of the brain is surprisingly uniform across all vertebrate taxa, as described above. Besides the development of structures for the processing of specialized senses such as the vagal and facial
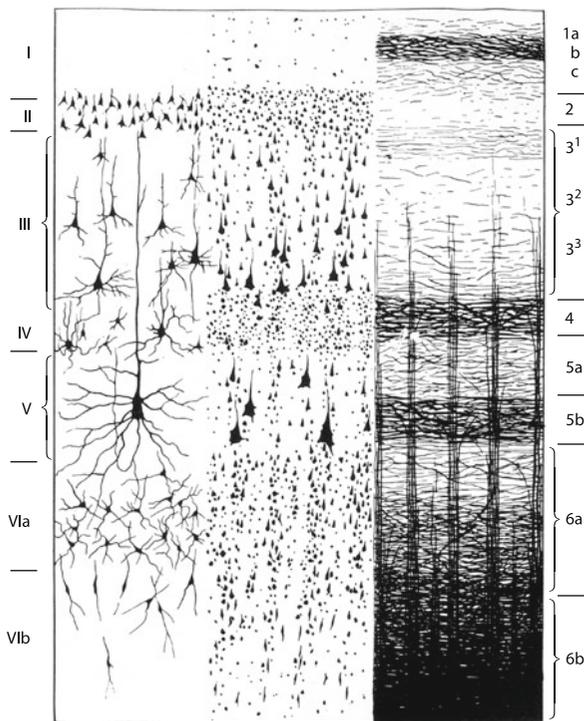
Fig. 2.23 Cytoarchitecture of the six-layered mammalian isocortex. The *left side* of the figure shows the distribution of nerve cells, predominantly pyramidal cells, in a Golgi staining. In the *middle*, the distribution of cell bodies is shown in a Nissl staining. The *right side* shows the distribution of myelinated fibers in a Weigert staining. *Roman numbers* to the *left* indicate the gross lamination of the cortex, *arabic numbers* to the *right* indicate the sublamination based on a Nissl staining (After Vogt and Brodmann from Creutzfeldt [40], modified, with permission)

lobe (taste) or the valvula cerebelli (electroreception) in teleost fishes, major changes are observed in the telencephalic roof, i.e., pallium or cortex. However, one of the most striking differences concerns absolute brain size (ABS), which in vertebrates varies from 1 mg (or mm^3) in miniaturized fishes and amphibians up to 8,000 g in the false killer whale, which is a range of almost seven orders of magnitude (Table 2.1).

The classes of craniates likewise differ markedly in brain size relative to body size (RBS) (Fig. 2.24). The smallest RBS is found in agnathans (myxinoids and petromyzontids), followed by bony fishes, amphibians, "reptiles", and cartilaginous fishes, the latter having surprisingly large brains. Mammals and birds, on average, have brains that are about ten times larger than those of the other groups of craniates of the same body size. In birds, parrots (Psittacidae) and corvids

(Corvidae) have 6–10 times larger brains than other birds. Among mammals, primates (with the exception of prosimians) generally have larger brains than the other orders with the same body size. In primates, prosimians and tarsiers have relatively small brains with an average of 6.7 g, followed by New World monkeys with an average of 45 g and Old World monkeys at an average of 115 g, with the largest monkey brains found in baboons. Among apes, gibbons have brain sizes (88–105 g) which fall within the range of Old World monkeys, while the large apes (orangutans, gorillas, chimpanzees) have brain weights between 330 and 570 g (males) [47].

Brain size in vertebrates is mostly determined (more than 90 %) by body size [48]. However, brain size does not increase proportionally with body size, but "lags behind", i.e., with an exponent (or allometric coefficient) of 0.6–0.8, which is due to the fact that with an increase in body size brains become absolutely larger, but relatively smaller – this is called *negative brain allometry* [44]. As a consequence, in small mice or insectivores brain volume may constitute 10 % or more of body volume, while in the blue whale, the largest living animal, the brain makes up only 0.01 % or even less of body mass [49]; (Fig. 2.25). Primates, in general, have higher RBS than all other groups of mammals.

The human brain has a weight of 1,250–1,450 g on average and represents about 2 % of body mass. Although the human brain is neither exceptional in ABS or RBS, it is unusually large in terms of body size. This can be demonstrated using various statistical methods, e.g., the encephalization quotient EQ, which indicates the extent to which the brain size of a given species E_a deviates from the expected brain size E_e;cf. [44]. Within primates, humans have the highest EQ of 7.4–7.8, meaning that the human brain is 7–8 times larger than that of an average mammal of the same body size (Table 2.1). They are followed by the monkeys *Cebus* and *Saimiri* with EQs of 4.8 and 2.8, respectively, while chimpanzees and orangutans have low (1.7 and 1.9, respectively) and gorillas very low EQs (1.5). Other mammals have EQs between 0.4 (rat) and 1.3 (elephant).

During mammalian brain evolution, all parts increased in size relative to the body, except the olfactory system. However, the telencephalon as well as the cerebellum underwent a faster growth than the other parts resulting in *positive allometry* (i.e., with an

Table 2.1 Brain weight, encephalization quotient, and number of cortical neurons in selected mammals

Animal taxa	Brain weight (in g)[a]	Encephalization quotient[b,c]	Number of cortical neurons (in millions)[d]
Whales	2,600–9,000	1.8	10,500
False killer whale	7,650		
African elephant	4,200	1.3	11,000
Homo sapiens	1,250–1,450[e]	7.4–7.8	15,000
Bottlenose dolphin	1,350	5.3	5,800
Walrus	1,130	1.2	
Camel	762	1.2	
Ox	490	0.5	
Horse	510	0.9	1,200
Gorilla	430[e]–570	1.5–1.8	4,300
Chimpanzee	330–430[e]	2.2–2.5	6,200
Lion	260	0.6	
Sheep	140	0.8	
Old World monkeys	41–122	1.7–2.7	840
Rhesus monkey	88	2.1	
Gibbon	88–105	1.9–2.7	
Capuchin monkeys	26–80	2.4–4.8	720
White-fronted capuchin	57	4.8	
Dog	64	1.2	160
Fox	53	1.6	
Cat	25	1.0	300
Squirrel monkey	23	2.3	450
Rabbit	11	0.4	
Marmoset	7	1.7	
Opossum	7.6	0.2	27
Squirrel	7	1.1	
Hedgehog	3.3	0.3	24
Rat	2	0.4	15
Mouse	0.3	0.5	4

[a]Data from Jerison, Haug, and Russell [44–46]
[b]Indicates the deviation of the brain size of a species from brain size expected on the basis of a "standard" species of the same taxon, in this case of the cat
[c]Data after Jerison and Russell [44, 46]
[d]Calculated using data from Haug [45]
[e]Basis for calculation of neuron number

exponent larger than 1; [50]). Inside the telencephalon, the cortex has grown faster both in surface and thickness. However, while the increase in surface was 10,000-fold (from 0.8 cm^2 in "insectivore"-like species to 7,400 cm^2 in whales), cortical thickness increased only slightly, from 0.5 mm in mice to 3 mm in *Homo sapiens*. Interestingly, mammals with much larger brains and consequently cortical surfaces such as elephants and cetaceans (whales and dolphins) have unusually thin cortices of 1.5 and 1 mm, respectively.

In all mammalian cortices, cortical cell density decreases with increasing cortex volume, but primates in general have higher densities (around 50,000 cells per mm^3) than expected compared to other mammals – elephants and cetaceans have the lowest cortical cell densities (6,000–7,000 cells per mm^3). Humans combine a relatively large brain, a very thick cortex with a relatively high cortical cellular density (about 30,000 cells per mm^3) which results in the fact that they have considerably more cortical neurons (about 15 billion) than elephants and cetaceans with their much bigger brains (11 and 10.5 billion, respectively), which is the highest number of cortical neurons found in animals [51, 52].
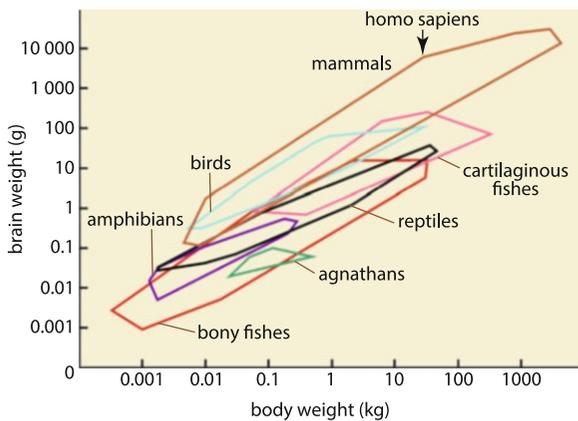
Fig. 2.24 **The relationship between brain weight** (ordinate, gram) **and body weight** (abscissa, kilogram) in the vertebrate classes in a double-logarithmic presentation using the polygon method developed by Jerison. Mammals and birds generally have larger relative brain weights or volumes than agnathans, bony fishes, amphibians, and "reptiles". The brains of cartilaginous fishes are in between. The weight/volume of the human brain is on top of the distribution, when corrected for body size. Further information in text (After Jerison [44], modified, with permission)

Fig. 2.25 **Mammalian brain size in percent of body size**. The figure shows brain weight as a percentage of body weight for the same 20 mammalian species as in Fig. 2.2, again plotted in log-log coordinates. As can be seen, small mammals such as mice and shrews have much larger brains in relative terms (10 % or more of body weight) than cetaceans (less than 0.01 %). Humans, with a brain representing 2 % of body weight, have a much higher relative brain size than expected (i.e., around 0.3 %) (From Dongen [49], modified, with permission)

2.4.1   Brain Evolution During Hominid Evolution

The earliest human-like primates, the australopithecines (such as "Lucy", *Australopithecus afarensis*) existed in East Africa at about 3–4 mya and had a brain volume of 400–450 cm³, which is equal to or only slightly larger than that of present chimpanzees (see Fig. 2.26). A strong increase in brain volume occurred only with the appearance of *Homo habilis* about 2 mya having 700 cm³. This means that brain size of our ancestors remained constant for 1.5 mya despite strong environmental changes. The next strong increase in brain size occurred 1.8 mya with the appearance of *Homo erectus*, who had a brain volume of 800–1,000 cm³. The appearance of early forms of *Homo sapiens* about 400,000 years ago with brain volumes between 1,100 and 1,500 cm³ represents the latest step of brain evolution in hominins. Importantly, not *Homo sapiens*, but *Homo neanderthalensis*, with 1,400–1,900 cm³ had the largest brain of all hominins and primates. The reasons for this dramatic increase in brain size in a relatively short evolutionary time are unclear despite a large number of scenarios.
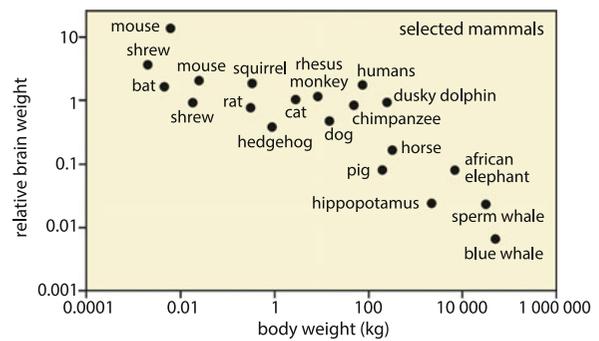
2.5   Brain and Intelligence

In humans, intelligence is commonly defined as mental capacities such as abstract thinking, understanding, communication, reasoning, learning, and memory formation, action planning, and problem solving [51]. Usually, human intelligence is measured by intelligence tests and expressed in intelligence quotient (IQ) values expressing different contents (e.g., visual-spatial, verbal, numerical). Evidently, such a definition and measurement of intelligence cannot be applied directly to nonhuman animals, because any test depending on verbalization is inapplicable. A number of comparative and evolutionary psychologists and cognitive ecologists converge on the view that mental or behavioral *flexibility* is a good measure of intelligence culminating in the appearance of novel solutions not part of the animal's normal repertoire [53, 54].

Intelligence defined in such a manner has developed several times independently during evolution, e.g., in cephalopods (e.g., *Octopus*), social insects (e.g., the honeybee), some teleost fishes (e.g., cichlids), some birds (corvids and parrots), and mammals. In all these cases, high intelligence is coupled with (*i*) larger to much larger brains as compared to less intelligent members of the respective taxon, (*ii*) specialized brain
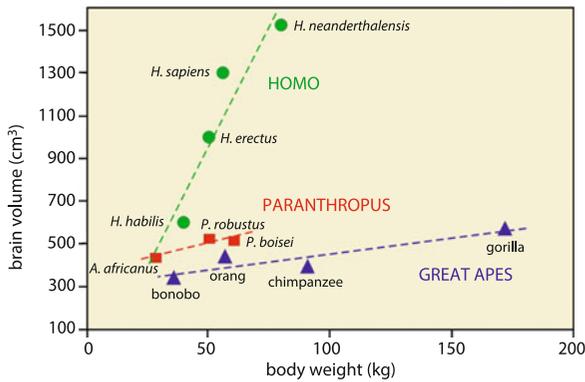
Fig. 2.26 **The relationship between body size and brain size or endocranial volume** (extinct species) in great apes (bonobo, chimpanzee, orangutan, gorilla), australopithecines (*Australopithecus africanus*, *Paranthropus robustus*, *P. boisei*), and the genus *Homo* (*Homo habilis*, *H. erectus*, *H. sapiens*, *H. neanderthalensis*) (Data from Jerison [44]). While in the great apes as well as in the extinct australopithecines brain/endocranial volume has increased only slightly with body size, in the genus *Homo* a steep increase in brain/endocranial volume has occurred during 2.5 mya culminating in the brain of the extinct *Homo neanderthalensis*, which with a volume of 1,200– 1,750 ccm was considerably larger than that of modern *Homo sapiens*

centers with a high number of densely packed and interconnected neurons, and (*iii*) structures and mechanisms for fast information processing, e.g., the vertical and subvertical lobe of *Octopus*, the mushroom bodies in the honeybee, the mesonidopallium of corvids, and the isocortex of primates. Primates are, on average, more intelligent than other mammals and all other animals, with the great apes and finally humans at the far end. Because of higher relative cortex volume and higher neuron packing density (NPD), primates have considerably more cortical neurons than other mammals of the same brain size. Likewise, information processing capacity (IPC) is generally higher in primates due to short interneuronal distance and high axon conduction velocity. Finally, primate cortices exhibit extensive parcellation according to the principle of intense local and sparse global connectivity [52].

Across taxa, differences in intelligence correlates best with differences in number of pallial or cortical neurons and synapses plus processing speed. The human brain combines large cortical volume with reasonable NPD, high conduction velocity, and high cortical parcellation. Cetaceans and elephants have much larger brains than even humans, but less cortical

neurons, because of much lower NPD. This could explain why cetaceans and elephants are not as intelligent as one would expect on the basis of brain size. The contrary is the case for corvid birds with very small brains, but high NPD and IPC, which could explain why these animals reveal an intelligence comparable to primates with much larger brains. All aspects of human intelligence are present at least in principle in nonhuman primates and in some other mammals and more distant vertebrates – except syntactical language. The latter can be regarded as a very potent "intelligence amplifier".

2.6   Convergence or "Deep Homologies"?

An unsolved question in the study of evolution, in general, and of nervous systems and brains, in particular, is the question whether the strikingly numerous cases of similar structures found in sense organs and brains are the result of true convergent evolution (*homoplasy*) or of the action of "deep" homologies (see below). Striking examples for convergent evolution in the traditional sense are the lens eye of *Octopus* and of vertebrates; the paired "ladder"-type ventral nerve cord of annelids and arthropods; and the tripartite brain in polychetes, arthropods, and (at least embryologically) craniates, among others.

The concept of "deep homologies" attempts to describe the role of very ancient genetic mechanisms governing growth and differentiation processes in metazoans [11]. This includes so-called *homeotic genes* that control the differentiation of organisms along their body axes, of sense organs, and nervous systems and brains. They are found to be the same in very distantly related animals such as the fruit fly *Drosophila* and the clawed toad *Xenopus*. In *Drosophila* (and all other insects studied) the formation of the ventral cords and the tritocerebrum, and in *Xenopus* (and all other chordates, including vertebrates) the development of the spinal cord and myelencephalon, is controlled by *Hox* genes. On the other hand, non*Hox* genes (*otd*/*Otx*) determine the formation of the proto- and deutocerebrum of insects and of the mes-, di-, and metencephalon in chordates. The zone in between these regions, the tritocerebrum in insects and the isthmic region in vertebrates, is controlled by so-called *Pax* genes in both groups [55]. These findings could now

be extended to all bilaterians and even to phyla having lost their bilateral organization in the adult stage (echinoderms), which leads to the assumption that all bilaterally organized animals possess a common "bauplan" for a tripartite brain since about 600 mya [11]. Precursors of such genes have been found even in coelenterates and sponges.

Such a new concept radically simplifies many problems concerning the evolution of nervous systems and brains, e.g., explaining the large number of seemingly "convergent" or "homoplastic" steps in the evolution of neural and sensory structures, because they appear to be based on the same regulatory developmental genes – this, however, leads to new problems, because an uncountable number of cases of secondary simplification have to be assumed. Even if there is a "deep" homology of such genes, the parts of the nervous systems and brains controlled by them may have developed independently, and the same or very similar developmental genes may have undergone a change in function. Furthermore, it is still unclear how the same regulatory genes can lead to very different structures. Insect and vertebrate brains have hardly any resemblance, and the same is true for the insect compound eye and the vertebrate lens eye, despite similar regulatory genes. These may represent basic organizational commands such as "form a tripartite brain!" or "develop a light-sensitive organ!", and it is left up to epigenetic (i.e., gene-expression regulating) mechanisms to form a pigment spot, a compound eye, or a lens eye.

2.7 Summary – Major Trends in the Evolution of Nervous Systems and Brains

At the level of bacteria and unicellular eukaryotes we already find a fundamental division into sensorium and motorium, with some sort of information processing in between, which involves a short-term memory and represents the basic organization of "cognitive" functions. In the earliest eumetazoans diffuse "basi-epithelial" nerve nets exist similar to that found in *Hydra*. From there, two major evolutionary trends took their course. The first represents a sidetrack leading to the evolution of ring-shaped nerve systems in cnidarians and ctenophorans ("coelenterates"), the other is the main track leading to a bilaterally organized nervous system with a circumesophageal ganglion and ventral cords having

originated already in Precambrian times 560 mya or earlier. Even planarians feature such a CNS, and at this level all extant neuronal mechanisms (including ion channels, synaptic mechanisms, and transmitters) were already present. Interestingly, both "coelenterates" and bilateral organisms possess very similar genes controlling the body plan – including the brain.

From the CNS of the most primitive bilaterally symmetric animals ("ur-bilateria"), again two major evolutionary trends originated – one in the protostomes, the other in the deuterostomes. The former split into two evolutionary lineages: the lophotrochozoan and the ecdysozoan schemes – in both lines we find the formation of complex sense organs and brains. Among lophotrochozoans, this is the case for predatory platyhelminths, polychaetes, and likewise predatory cephalopods. Here we find complex lens eyes and visual systems as well as a multilobed supraesophageal ganglia, and the brain of *Octopus* is regarded the most complex protostome brain. Among ecdysozoans, arthropods likewise exhibit highly complex sense organs and brains, and those of the flies and hymenopterans (wasps, bees, ants) are considered the most complex ones. The deuterostomes, with an unresolved phylogenetic origin, likewise exhibit two major developmental lineages, one leading to the Echinodermata with radially symmetric adult nervous systems superficially resembling those of the "coelenterates"; the other line leading via hemi-, uro-, and cephalochordates – all with very simple nervous systems – to the craniates and eventually to the vertebrates. The vertebrate brain evolved very early (about 500 mya) and since then remained relatively uniform in its basic organization. Major evolutionary changes concerned the specialization, complication, and enlargement (sometimes reduction) of the different brain regions and formation of novel sensory systems such as gustatory, electroreceptive, infrared, echolocation, and visual systems. The most dramatic changes occurred in the dorsal telencephalon (pallium, cortex) together with related changes in the dorsal thalamus projecting to this structure.

Birds and, independently, mammals evolved unimodal afferents to the pallium-cortex – in birds mostly to the dorsal ventricular ridge and in mammals to the isocortex forming topographically organized sensory and motor areas. In birds as well as in mammals there is a dramatic increase in brain size and in the size of the pallium and isocortex, in particular. Among birds the largest brains are found in psittacids and corvids

and among mammals the largest brains occur in primates (in all cases corrected for body size) and this correlates roughly with the degree of cognitive abilities such as learning, problem solving, use and fabrication of tools, imitation, insight, thinking, action planning, and language. Humans have the largest brain of all animals (corrected for body size) and in addition they have the largest number of cortical neurons as well as the most efficient information-processing capacities among large-brained animals and so far appear to be the only lifeform with a grammatically and syntactically structured language.

References

1. Futuyma DJ (2009) Evolution, 2nd edn. Sinauer, Sunderland
2. Raff R (1996) The shape of life. Genes, development, and the evolution of animal form. University of Chicago Press, Chicago
3. Hennig W (1966, 1979) Phylogenetic systematics. University of Illinois Press, Urbana
4. Ghysen A (2003) The origin and evolution of the nervous system. Int J Dev Biol 47:555–62
5. Berg HC (2000) Motile behavior of bacteria. Phys Today 53:24–9
6. Armus HL, Montgomery AR, Jellison JL (2006) Discrimination learning in paramecia (*Paramecium caudatum*). Psychol Rec 56:489–98
7. Lichtneckert R, Reichert H (2007) Origin and evolution of the first nervous systems. In: Kaas J, Bullock TH (eds) Evolution of nervous systems. A comprehensive review, vol 1, Theories, development, invertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 289–315
8. Bullock TH, Horridge GA (1965) Structure and function in the nervous system of invertebrates. Freeman, San Francisco
9. Satterlie RA, Spencer AN (1983) Neuronal control of locomotion in hydrozoan medusae. J Comp Physiol 150:195–206
10. Grimmelikhuijzen CJP, Carstensen K, Darmer D, McFarlane I, Moosler A, Nothacker HP, Reinscheid RK, Rinehart KL, Schmutzler C, Vollert H (1992) Coelenterate neuropeptides: structure, action and biosynthesis. Am Zool 32:1–12
11. Hirth F, Reichert H (2007) Basic nervous system types: one or many. In: Striedter GF, Rubenstein JL (eds) Evolution of nervous systems. Theories, development, invertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 55–72
12. Moroz LL (2009) On the independent origins of complex brains and neurons. BBE 74:177–90
13. Paulus HF (1979) Eye structure and the monophyly of the arthropoda. In: Gupta AP (ed) Arthropod phylogeny. Van Nostrand Reinhold, New York
14. Hennig W (1972) Taschenbuch der speziellen Zoologie, Teil 2, Wirbellose II. H Deutsch, Frankfurt
15. Kandel ER (1976) Cellular basis of behavior – an introduction to behavioral neurobiology. WH Freeman, New York
16. Young JZ (1971) The anatomy of the nervous system of *Octopus vulgaris*. Clarendon, Oxford
17. Nixon M, Young JZ (2003) The brains and lives of cephalopods. Oxford Biology, Oxford
18. Shomrat T, Zarrella I, Fiorito G, Hochner B (2008) The octopus vertical lobe modulates short-term learning rate and uses LTP to acquire long-term memory. Curr Biol 18:337–42
19. Brenner S (1974) The genetics of *Caenorhabditis elegans*. Genetics 77:71–94
20. White JG, Southgate E, Thomson JN, Brenner S (1976) The structure of the ventral nerve cord of *Caenorhabditis elegans*. Phil T Roy Soc B 275:327–48
21. Schafer WR (2005) Deciphering the neural and molecular mechanisms of *C. elegans* behavior. Curr Biol 15:R723–9
22. Withington PM (2007) The evolution of arthropod nervous systems; insight from neural development in the Onychophora and Myriapoda. In: Kaas J, Bullock TH (eds) Evolution of nervous systems. A comprehensive review, vol 1, Theories, development, invertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 317–36
23. Kästner A (1969) Lehrbuch der speziellen Zoologie, Band I, Wirbellose 1. Teil. G Fischer, Stuttgart
24. Foelix RF (2010) Biology of spiders, 3rd edn. Oxford University Press, Oxford/New York
25. Mobbs PG (1984) Neural networks in the mushroom bodies of the honeybee. J Insect Physiol 30:43–58
26. de Marco RJ, Menzel R (2008) Learning and memory in communication and navigation in insects. In: Byrne JH, Menzel R (eds) Learning theory and behavior, vol 4, Learning and memory: a comprehensive reference. Academic (Elsevier), Amsterdam/Oxford, pp 477–98
27. Strausfeld NJ, Strausfeld C, Loesel R, Rowell D, Stowe S (2006) Arthropod phylogeny: onychophoran brain organization suggests an archaic relationship with a chelicerate stem lineage. Proc Biol Sci 7:1857–66
28. Holland LZ, Short S (2008) Gene duplication, co-option and recruitment during the origin of the vertebrate brain from the invertebrate chordate brain. BBE 72:91–105
29. Nieuwenhuys R, ten Donkelaar HJ, Nicholson C (1998) The central nervous system of vertebrates, 3rd edn. Springer, Berlin/Heidelberg/New York
30. Striedter GF (2005) Brain evolution. Sinauer, Sunderland
31. Northcutt RG (1987) Brain and sense organs of the earliest vertebrates: reconstruction of a morphotype. In: Foreman RE, Gorbman A, Dodd JM, Olsson R (eds) Evolutionary biology of primitive fishes, vol 103, NATO ASI series, series A: life sciences. Plenum, New York
32. Northcutt RG (1989) Brain variation and phylogenetic trends in elasmobranch fishes. J Exp Zool Suppl 2:83–100
33. Romer AS, Parson TS (1986) The vertebrate body. Saunders College Publishing, Philadelphia
34. Wullimann MF, Vernier P (2007) Evolution of the nervous system in fishes. In: Kaas J, Bullock TH (eds) Evolution of nervous systems. A comprehensive review, vol 2, Non-mammalian vertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 39–60
35. Dicke U, Roth G (2007) Evolution of the amphibian nervous system. In: Kaas JH, Bullock TH (eds) Evolution of nervous systems. A comprehensive review, vol 2, Non-mammalian vertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 61–124

36. Nieuwenhuys R, Voogd J, van Huijzen C (1988) The human central nervous system. Springer, Berlin/Heidelberg/New York

37. Karten HJ (1991) Homology and evolutionary origins of the "neocortex". Brain Behav Evol 38:264–72

38. Reiner A, Yamamoto K, Karten HJ (2005) Organization and evolution of the avian forebrain. Anat Rec A 287A: 1080–102

39. Medina L (2007) Do birds and reptiles possess homologues of mammalian visual, somatosensory, and motor cortices. In: Kaas J, Bullock TH (eds) Evolution of nervous systems. A comprehensive review, vol 2, Non-mammalian vertebrates. Academic (Elsevier), Amsterdam/Oxford, pp 163–94

40. Creutzfeldt OD (1983) Cortex Cerebri. Leistung, strukturelle und funktionelle Organisation der Hirnrinde. Springer, Berlin/Heidelberg/New York

41. Kaas JH (2007) Reconstructing the organization of neocortex of the first mammals and subsequent modifications. In: Kaas JH, Krubitzer LA (eds) Evolution of nervous systems. A comprehensive review, vol 3, Mammals. Academic (Elsevier), Amsterdam/Oxford, pp 27–48

42. Changizi MA (2007) Scaling the brain and its connections. In: Kaas JH, Krubitzer LA (eds) Evolution of nervous systems. A comprehensive review, vol 3, Mammals. Academic (Elsevier), Amsterdam/Oxford, pp 167–80

43. Güntürkün O (2008) Wann ist ein Gehirn intelligent? Spektrum der Wissenschaft 11:124–132

44. Jerison HJ (1973) Evolution of the brain and intelligence. Academic, Amsterdam/Oxford

45. Haug H (1987) Brain sizes, surfaces, and neuronal sizes of the cortex cerebri: a stereological investigation of man and his variability and a comparison with some mammals (primates, whales, marsupials, insectivores, and one elephant). Am J Anat 180:126–42

46. Russell S (1979) Brain size and intelligence: a comparative perspective. In: Oakley DA, Plotkin HC (eds) Brain, behavior and evolution. Methuen, London, pp 126–53

47. Falk D (2007) Evolution of the primate brain. In: Henke W, Tattersall I (eds) Handbook of paleaanthropology. Primate evolution and human origins, vol 2. Springer, Berlin, pp 1133–62

48. Hofman MA (2000) Evolution and complexity of the human brain: some organizing principles. In: Roth G, Wullimann MF (eds) Brain, evolution and cognition. Spektrum Akademischer Verlag, Heidelberg, pp 501–21

49. van Dongen PAM (1998) Brain size in vertebrates. In: Niewenhuys R (ed) The central nervous system of vertebrates. Springer, Berlin/Heidelberg/New York, pp 2099–134

50. Pilbeam D, Gould SJ (1974) Size and scaling in human evolution. Science 186:892–901

51. Roth G, Dicke U (2005) Evolution of the brain and intelligence. Trends Cogn Sci 9:250–7

52. Roth G, Dicke U (2012) Evolution of the brain and intelligence in primates. Prog Brain Res 195:413–30

53. Byrne R (1995) The thinking ape. Evolutionary origins of intelligence. Oxford University Press, Oxford/New York

54. Gibson KR, Rumbaugh D, Beran M (2001) Bigger is better: primate brain size in relationship to cognition. In: Falk D, Gibson KR (eds) Evolutionary anatomy of the primate cerebral cortex. Cambridge University Press, Cambridge/New York, pp 79–97

55. Farris SM (2008) Evolutionary convergence of higher brain centers spanning the protostome-deuterostome boundary. Brain Behav Evol 72:106–22