

Invertebrate Nervous Systems

Thomas Matheson, *University of Cambridge, Cambridge, UK*

The nervous systems of invertebrates are smaller and contain fewer neurons than those of vertebrates, yet they generate the great diversity and complexity of behaviour that has contributed to the incredible success of these animals.

Introduction

Invertebrates are not 'simple animals', but they are indeed masters of economy: their small nervous systems contain many fewer nerve cells than those of even the tiniest vertebrates, yet these animals solve all of the same survival problems, can live in highly organized societies and can communicate complex messages. The goal of this article is to outline general features of the nervous systems of invertebrates, and to begin to ask how these tiny information-processing systems drive such diverse behaviour.

Components of a Nervous System

A nervous system can be thought of as an organized collection of neurons that interact at points of contact called synapses. Neurons are electrically excitable cells whose membranes can generate and transmit changes of voltage that form a signal. These changes in voltage can be graded in amplitude or all-or-nothing events of fixed amplitude called action potentials. Synapses are points where the membranes of two or more neurons come very close together, associated with specialized features of the membranes. Electrical signals in one cell may be passed directly to other cells at electrical synapses, or more often are converted into chemical signals that diffuse across a tiny synaptic gap that remains between the membranes. Communication between neurons may also take place without synapses, through long distance chemical transmission, but no known nervous system functions in the absence of the ubiquitous synapse.

The cellular components of an invertebrate nervous system include: sensory neurons, which convert physical variables (e.g. light level or muscle force) into electrical signals; motor neurons, which make synapses with muscles or other effector organs (e.g. light-producing organs, glands); interneurons, which transmit information between other neurons; and glia, which are electrically inexcitable cells that influence the ionic environment surrounding neurons and the transmission of signals between them. In sponges and cnidarians, in particular, the distinctions between neuron types may break down,

Introductory article

Article Contents

- Introduction
- Components of a Nervous System
- Neuroid Systems in Sponges
- Simple Nerve Nets
- Nervous Systems: Central and Peripheral Components
- Segmentally Organized Nervous Systems
- Invertebrate Brains
- Protochordate Nervous Systems
- Mechanisms to Cope with Environmental Change

with some cells carrying out sensory, motor and inter-neuronal functions.

In invertebrates, unlike vertebrates, the somata of motor neurons and interneurons are not important sites of synaptic input. Instead they give rise to a single primary neurite that enters the core of the ganglion and divides into dendritic and axonal regions. The distinction between input and output regions is often quite blurred, and in most cases it is possible to find input and output synapses adjacent to one another. Nevertheless, the ratio of input to output synapses differs on different branches of a neuron, so it is usually possible to distinguish input and output regions.

The ability of neurons to generate and transmit electrical signals, and for these signals to pass between cells, be summed, multiplied and transformed by different types of cells and synapses, enables nervous systems to process information. Changes in the environment are detected by sensory structures, encoded in the activity of neurons, analysed for relevance against the backdrop of previous experience, transmitted through the nervous system, and used to drive appropriate actions. The actions may be compensatory (e.g. postural) or active (e.g. generating locomotion, or producing a sound). Many of these behavioural actions are completed in fractions of a second, limited only by the speed of neuronal activity; whereas others take place over hours, days or even the lifetime of the animal. These long-term changes in neuronal function can depend on neurohormonal chemical signals, or on morphological changes in the neurons and their inter-connections. How are all these functions carried out in different invertebrates?

Neuroid Systems in Sponges

Sponges (Parazoa) do not have true nervous systems composed of sensory, motor and interneurons, yet they exhibit behaviour. In the Porifera (cellular sponges) this is limited to noncoordinated beating of the flagella and an

ability to contract myocytes that regulate the diameter of water outflow pores, called oscula. Responses of the oscula myocytes to touch are entirely local. In contrast, the flagellar beating of hundreds of cells in syncytial sponges (Symplasma) can be stopped and started in a coordinated way by electrical impulses that are elicited by touch on the body, or by particles in the inflow water stream. The impulses propagate throughout the syncytial trabecular reticulum, which makes close contact with the flagellated tissue through cytoplasmic bridges. There are no true synapses.

Simple Nerve Nets

Nerve nets are characteristically found in jellyfish, corals, hydroids and comb jellies (Cnidaria and Ctenophora). In the simpler forms they consist of diffuse networks of neurons interconnected by chemical or electrical synapses, or by syncytial contacts (Figure 1a). In more complex forms, neurons are bundled together into loose nerve tracts or plexuses that are key sites of neuronal integration; and there may be considerable specialization of function between different parts of the nervous system. For example, there may be separate neuronal pathways for escape and nonescape swimming. There can even be two or more distinct nerve nets.

The neurons may be multifunctional, combining sensory, motor and interneuronal features. Many do not have distinguishable input (dendritic) and output (axonal) branches, so conduction occurs in both directions. Some others, however (e.g. in *Hydra*), are polarized so that sensory stimuli are detected at one pole and signals are transmitted along axons to the other end of the neuron. There is considerable differentiation among the neurons so that particular subgroups can have different functions. Pacemaker neurons with an intrinsic rhythm of activity are responsible for generating the swimming rhythms in scyphomedusae. Sense organs include mechanoreceptors, photoreceptors and statocysts (to detect orientation relative to gravity).

Neuronal action potentials in nerve nets are driven primarily by sodium and potassium currents, as is the case in more complex nervous systems. Other neurons convey signals not as action potentials but as graded changes in membrane potential. Remarkably, some neurons in jellyfish can transmit sodium action potentials under some conditions, but calcium potentials under others, leading to two distinct patterns of swimming behaviour. Conduction velocities can differ between neurons, with important consequences for the coordinated control of behaviour. Synapses show spatial and temporal summation, which increase greatly their ability to modify the flow of information between cells. Many synapses transmit in both directions, having neurotransmitter vesicles on both sides of the synapse. This contrasts to the situation in other

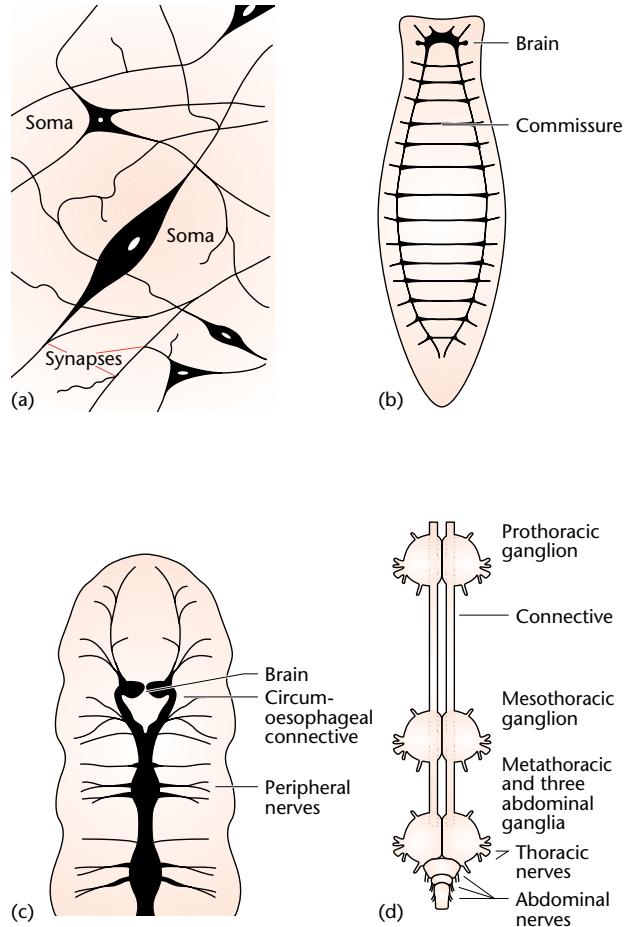


Figure 1 Different types of invertebrate nervous systems. (a) A simple nerve net of loosely associated neurons in a sponge connected at points of contact by synapses (high magnification view). (b) The ladder-like layout of a flatworm, with two longitudinal connectives running the length of the body, joined at intervals by commissures. (c) The segmentally organized nervous system of an annelid, with the longitudinal connectives and ganglia fused along the midline. There is an elongated ganglion for each segment. (d) Three ganglia located in the segmented thorax of an insect. The 'metathoracic ganglion' is really a fused structure containing neurons of the metathoracic ganglion and the first three abdominal ganglia.

invertebrates, where unidirectional transmission is more usual. There is a wide variety of transmitters and neuroactive substances, particularly peptides, all of which occur in particular subsets of the neurons.

All of this complexity endows these animals with the ability to carry out a remarkable range of behaviours. Some sea anemones can detect the presence of a hermit crab and climb onto its shell for a ride. Others detach themselves from the substrate and swim to avoid predators. The ability of these animals to modify their behaviour (learn) is less clear, although there is good evidence for habituation and sensitization.

Nervous Systems: Central and Peripheral Components

In the sponges and Cnidaria there is no clear distinction between central and peripheral components of the nervous system. In invertebrates belonging to the Bilateria, and in vertebrates, however, it is possible to distinguish between central nervous system (CNS) and peripheral nervous system (PNS). The CNS is an aggregation of neuronal components organized into longitudinal or ring-like nerve cords, usually near the midline. This includes the somata and dendrites of motor neurons, and all interneurons. The output branches of sensory neurons also ramify into the CNS. The peripheral nervous system includes sensory neurons, whose somata are generally, but not exclusively, found outside the central ganglia, and the nerves leading to and from the CNS (although they may contain axons of both sensory and motor neurons). Small specialized ganglia associated with the gut, for example, fall into an intermediate category, in that they contain motor neurons and interneurons, but act somewhat independently of the CNS. Very generally, the PNS carries sensory information from the periphery to the CNS and carries motor signals back in the other direction; but it is argued below that the PNS does rather more than this.

Much of what we think of as neuronal integration (i.e. the processing of information as it passes along and between neurons) takes place in those regions of the CNS that contain richly interconnected networks of input and output branches of diverse neuron types. These neuropil regions are a feature of the CNS that is not present in the PNS. Synapses between neurons (as opposed to those made by neurons onto muscles) are relatively rare in the PNS. Exceptions include inhibitory synapses made onto the axons of motor neurons in crustacea and insects, and synapses between the axons of sensory neurons in a specialized glomerulus in a leg nerve of the fruitfly. In the latter case, the many peripheral synaptic connections in the glomerulus may provide a mechanism for the PNS to supply the CNS with preprocessed sensory information. In animals with a CNS the flow of information from sensory receptors to a final motor action virtually always passes through the CNS, whether in a monosynaptic reflex loop that connects a sensory neuron directly to its target motor neurons, or through longer pathways involving many interneurons. The key advantage of this centralized integration is that actions can be coordinated in the face of potentially conflicting signals and motor requirements. It is a mistake, however, to consider the PNS simply as a conglomeration of sensors and effectors, with the CNS doing all the computation. The specific response properties of each individual sensory neuron (threshold, adaptation rate, adequate stimulus) coupled with the overall patterns of activity across populations of receptors, endows the PNS with important computational abilities. For example,

the overall activity of populations of auditory receptors tuned to different sound frequencies in an insect may filter and enhance behaviourally relevant sound patterns.

In the peripheral motor system, output terminals of motor neurons and the muscles that they innervate are both important targets for neuromodulatory substances. There are interactions between the patterns of motor activity, these neuromodulators, and the dynamic properties of the muscles themselves. This means that any motor signal from the CNS is always modified in the periphery to produce a finely tuned response. Once again we see that the PNS is an important site for integration.

Segmentally Organized Nervous Systems

The bodies and nerve nets of Cnidaria and Ctenophora can be thought of as a flat sheet that has been contorted into a three-dimensional form in which neuronal activity can propagate in many directions simultaneously. In many other taxa, however, the body has developed a more pronounced longitudinal form with bilateral symmetry. Locomotion is generally polarized, so one end of the animal is the front; and with this comes an almost inevitable accumulation of sensory receptors at this end. This elongation and regional specialization has in turn been accompanied by differing degrees of segmentation of the body into repeated units in, for example, annelids and arthropods. The echinoderms have instead developed radial symmetry, and molluscs have developed complex nonmetamerically segmented nervous systems. In segmented invertebrates the layout of the nervous system to a large extent reflects the degree of body segmentation, so that each body segment is innervated by a corresponding segment of the CNS.

In the nonsegmented flatworms there are nevertheless clear repeating patterns of nervous organization. The anterior brain gives rise to bilaterally paired longitudinal connectives that run the length of the body, joined periodically across the midline by commissures (**Figure 1b**). The overall result is a ladder-like arrangement of the main elements of the CNS, with side branches (nerves) leading off to the periphery.

In annelids and arthropods the segmentation of the body is much more clearly defined, as is that of the nervous system. Bilaterally paired connectives are linked together across the midline by one or more commissures per segment. At these important junctions each segment has an expanded mass of neurons that forms a ganglion (**Figure 1c**). Within a segment these bilaterally symmetrical ganglia can be relatively separate, joined across the midline by a long commissure; or they can be tightly fused together on the midline (as in **Figure 1c**) so that the commissure becomes an internal structure that is not evident except in histological sections. This trend towards midline fusion is

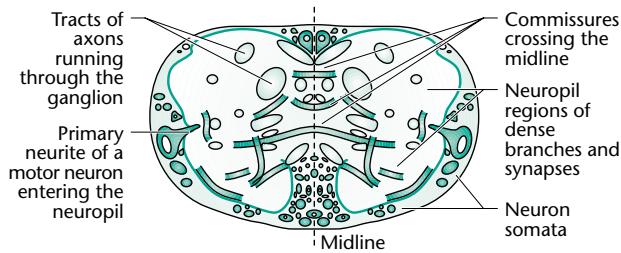


Figure 2 Cross-section through an insect ganglion to show longitudinal bundles (tracts) of axons, neuron somata in a layer around the margin, commissures containing branches of neurons that cross the midline, and the remaining areas of neuropil where almost all of the fine branches and synapses are found. In a large insect like a locust, a ganglion measures about 1 mm across.

evident in some annelids, and is the norm in arthropods. In most annelids each ganglion is diffuse and extends along the connectives for most or all of the length of the body segment, so that it merges with the immediately anterior and posterior ganglia. In other annelids and in most arthropods the ganglion of each segment is much more condensed so that those in adjacent segments are separated by relatively long connectives. Secondarily, however, there has been a trend towards re-fusion of many of these condensed ganglia (**Figure 1d**), which will be dealt with below.

Ganglionic structure follows a common pattern in virtually all invertebrates, with an outer rind of neuronal somata surrounding an inner core of axons and dendrites (**Figure 2**). The somata are clustered in groups, each derived from a common neuronal ancestor neuroblast cell. The axonal processes of motor neurons leave the ganglion through the lateral nerves to innervate their targets in the periphery (often muscles). Most motor neurons have just one axon leaving the ganglion, but a few have axons in several nerves that innervate different targets. In this way a single motor neuron can exert coordinated control over sets of muscles that need to act together. Individual muscles are generally innervated by just one or a few excitatory motor neurons and by a similar number of inhibitory motor neurons. Interneurons may be local, with all their branches restricted to their segment of origin, or intersegmental, with branches in two or more segments and an axon (or axons) in the longitudinal connectives. Neuromodulatory neurons can be either interneuronal in morphology, so that their actions take place entirely within the ganglion, or they can have axons to the periphery where they regulate muscle or motor output. Neurosecretory neurons that act by releasing neuroactive substances not at synapses but into the haemolymph (blood) have axons that leave the ganglion to innervate special neurohaemal release sites, which are often in the form of dense regions of branching that cover large surface areas of the lateral nerves. The axons of sensory neurons whose somata are in the periphery enter the ganglion through the lateral nerves

(which therefore often contain both sensory and motor axons) and branch in the core neuropil regions. Here they primarily make output synapses with motor and interneurons, but it is increasingly clear that they also receive many input synapses from interneurons that can exert powerful influences on the transmission of sensory information.

The core of the ganglion, as just described, therefore contains bundles of primary neurites arriving from the somata in the rind, regions of dense fine branches where most of the synapses are made (neuropils), and bundles of axons exiting (motor) or entering (sensory) the core through the nerves. In addition, there are longitudinal bundles (tracts) of axons, some of which enter the connectives to pass into anterior or posterior ganglia. Depending on the degree of fusion of the two bilaterally paired ganglia at the midline there are either bundles of axons entering the commissures that cross the midline or, where the ganglia are tightly fused as in insects, there will be many smaller bundles crisscrossing the midline in distinct groups. This increase in the number of commissures, and the shortening of their length in fused ganglia, is likely to be one of the key advantages of ganglionic fusion. Information can more easily and rapidly be passed between the two sides so that bilateral coordination can be much more sophisticated. This may be particularly important for legged animals where coordination must be more highly organized than that in worms, for example.

Segmentation is driven by the expression of so-called homeotic genes that are conserved across phyla. Differential expression of combinations of these genes in different segments leads to variations on the basic theme. In insects, for example, the larval mesothoracic segment can be thought of as representing an ancestral pattern of organization, with other segments being specialized in different ways. What this means is that it is possible to find equivalent 'homologous' neurons in many segments. These may have similar morphology, patterns of synaptic connections, neurotransmitter content, and function. In those arthropods that have come to be used as model systems for the study of neuronal function, some of these serially repeated neurons can be recognized as individual cells, and their roles studied not only in different body segments but repeatedly in different animals of the species. Such is the conservation of form and function that particular neurons can even be recognized in different species. Examples of this from the insects include leg motor neurons, visual interneurons and local nonspiking interneurons that can be recognized in stick insects and locusts. For obvious technical reasons most identified neurons are those with easily recognizable shapes or functions, but for the majority of neurons it is technically impossible to determine unambiguously if they represent unique individuals that appear reliably across animals or species. Nevertheless, there is a general expectation that many (perhaps most) neurons are strongly conserved.

A key feature of the organization of segmented nervous systems in annelids and arthropods is a trend towards fusion of ganglia along the longitudinal axis, particularly at the head. This fusion is not to be confused with the ancestral state found in some oligochaetes, where segmental ganglia are simply ill defined and tend to run into one another without a complex pattern of well-organized tracts and commissures. A fused ganglion in an insect or crustacean contains distinct remnants of the two or more ancestral ganglia from which it has evolved. Many or all of the ancestral lateral nerves may be present, and the internal structure reveals many of the serially repeated commissures and neuropils. The fusion, however, has important consequences, akin to those described for bilateral fusion above. Conduction distances are reduced, increasing the speed with which information can be processed. More importantly, interneurons in particular can span segmental boundaries to collate and relay information from more diverse sources, increasing their power of computation. The pinnacle of ganglionic fusion occurs in the brain, and will be dealt with below.

Invertebrate Brains

The evolution of bilateral symmetry and predominantly forwards locomotion in invertebrates has meant that one end of the animal (the head) encounters new features of the environment before the rest of the body. To best detect signals from the environment there has been an accumulation of sensory structures at the front, and to maximize feeding efficiency the mouthparts often occur here also. These adaptations have driven many specializations of the anterior ganglia to form a brain.

So what is it that distinguishes the brain from the remaining ganglia of the nerve cord? First, it is the primary neuronal structure anterior to the mouth (it is linked to the rest of the CNS by the circumoesophageal connectives). The next ganglion (the suboesophageal ganglion) is often also specialized, and for some purposes it can be considered together with the brain as having overall coordinating functions (they are referred to collectively as the cephalic ganglia). Second, the brain contains conspicuous regions of neuropil largely devoted to the processing of sensory information from the many highly specialized receptors on the head, including eyes and antennae where present. There are few motor neurons. Third, it is derived evolutionarily from the fusion of several segmental ganglia (as the head itself is a complex fusion of segments). In a locust, for example, the central part of the brain has 73 named commissures, compared to 10 per thoracic ganglion. The great extent of fusion in the brain and the distortions caused by the expansions of sensory neuropils make it virtually impossible to identify clearly the remnants of each ancestral ganglion in the most complex brains. The fourth key feature of the brain is the presence of so-called corpora

pedunculata, or mushroom bodies, in invertebrates as diverse as polychaetes and insects. These are bilaterally paired regions of the brain containing vast numbers of tiny neurons whose role is thought to be in multimodal integration and, in insects, associative learning. There are in excess of 1 million neurons in this region in the brain of a bee, presumably providing a richly interconnected network that underlies in part the remarkable social, communication and learned behaviours of these insects. The brain of an octopus (a cephalopod mollusc) is subdivided into numerous lobes that are clearly distinguishable from one another on both structural and functional grounds. For example, the neuropil regions of different lobes can have quite different patterns of organization. The optic lobes alone contain some 65 million neurons. The extreme cephalization and great evolutionary distance of the cephalopods from even other molluscs makes any search for homology extremely difficult.

The brain clearly has a role in providing overall coordination of behaviour (particularly selecting between behaviours), but it would be wrong to think that without a brain there can be no behaviour at all! In fact, removing the brain causes hyperactivity in many invertebrates, suggesting that one of its key roles is to suppress many behaviours that are actually generated further posterior in the nerve cord. Examples include egg laying in some insects and locomotion in oligochaetes. This also emphasizes the fact that quite sophisticated behaviours can be carried out in the absence of a brain. Decerebrate locusts can make precisely targeted scratching movements with their legs to brush away irritating objects that touch their bodies, while decerebrate earthworms crawl, eat and copulate. The patterns of motor activity that produce these behaviours, and their regulation by ongoing sensory feedback, are therefore generated by neuronal networks that reside solely in more posterior parts of the nerve cord.

Although the brain has important inhibitory effects on many behaviours, a second key role is to initiate other, usually more complex, behaviours. Among important examples across phyla are searching for food and searching for mates. A closely related function of the brain is to control the overall state of arousal of the animal. A third role is in learning and memory, but it is important here to distinguish between the simplest forms of sensitization and habituation that are widespread in nervous systems and the more sophisticated types of associative learning that are the province of the brains of more complex invertebrates.

Protochordate Nervous Systems

Two groups of invertebrates, the tunicates and the lancelets, are grouped with the vertebrates as chordate animals, and give us an important insight into early stages

in vertebrate evolution. Their nervous systems are most easily described by reference to the vertebrate plan, but they are described here briefly for completeness. The protochordates are bilaterally symmetrical and, at some stage of their life history, possess an internal skeletal rod, the notochord, which is a key defining feature of all chordates. In tunicates this is present only in the larval stage. The nervous system of an adult tunicate is recognizably invertebrate in layout, in that it consists of a ganglion with nerves that radiate out to innervate the siphons, mantle and muscles. In the lancelet *Amphioxus*, however, the adult central nervous system is a hollow dorsal cord that much more closely resembles a vertebrate nervous system. It is modified somewhat at the front end into a cerebral vesicle, and although this is not an elaborate brain, recent genetic studies show clearly that it has great homology with vertebrate brain structure. There is a simple anterior eyespot that has been proposed to be homologous with vertebrate eyes, and different regions of the cerebral vesicle are thought to be homologous with the vertebrate forebrain, midbrain and hindbrain, respectively. Sensory neuron somata lie within the CNS, which differs from the situation in both vertebrates (where they mostly lie in the spinal ganglia) and in other invertebrates, where most lie in the periphery. The muscles are unusual in that they send processes into the CNS, where they receive motor inputs, rather than having motor axons extending out to them. The neurobiology of protochordates is relatively poorly understood, despite their clear importance for our understanding of both invertebrate and vertebrate evolution.

Mechanisms to Cope with Environmental Change

The nervous systems of even the simplest invertebrates are richly interconnected networks containing many neurons with different physiological properties. To function properly (and thus ensure survival of the animal) the actions and interactions of all these cells, and of the sensory receptors and the muscles, must be carefully coordinated. Vertebrates, particularly the warm-blooded homeotherms, expend considerable energy maintaining a stable internal physiological environment within which their organ systems, including the nervous system, are shielded from fluctuations in the environment. Clearly this must help prevent potentially disastrous disruptions to neuronal function. Although invertebrates also control many aspects of internal physiology, they do not have the same sophisticated ability to control their body temperature. Since physiological processes slow down as temperature falls, the behaviour of invertebrates and cold-blooded vertebrates is particularly susceptible to cold, and yet many are found in polar seas at the freezing point of water, and

others tolerate subzero temperatures in alpine zones. Even the temporal resolving power of an insect eye is compromised by a fall in temperature, so that the insect's view of the moving world must be blurred significantly in the cold. How can invertebrates survive extremes of cold where they may compete with or be preyed on by warm-blooded vertebrates that do not face the same problems?

The key problem for invertebrates in cold environments is that the rate of conduction of action potentials in nerve cells slows down. In many cases this is simply followed by a slowing down of all the animal's behaviours. In others, however, compensatory mechanisms come into play. Some animals can behaviourally thermoregulate to maintain a body temperature a little above that of the environment by seeking out the warmth of the sun, for example. Others, such as hoverflies, use heat produced by the flight muscles to warm the head and brain (in this case helping to solve the visual blurring problem!). Many invertebrates possess some large diameter axons, which conduct more rapidly than thin ones. This culminates in the giant axons of squid, whose diameters may exceed 1 mm. Giant axons are vital in coordinating rapid escape movements in invertebrates ranging from earthworms to crayfish, and must be important in enabling these animals to survive attacks by warm-blooded predators. Another mechanism to speed up conduction rates is to wrap axons in thick layers of glial cells, as is the case in some marine crustacea (copepods). At a biochemical level, invertebrates adapt to changes in temperature by regulating the biophysical make-up of their neuronal cell membranes. Changes in membrane composition (primarily the ratio of saturated to unsaturated fatty acids) affect the generation and transmission of action potentials, thus allowing neuronal function to be stabilized to some extent as temperature varies.

Further Reading

- Barnes RSK, Calow P, Olive PJW, Golding DW and Spicer JI (2001) *The Invertebrates: A Synthesis*, 3rd edn. Oxford: Blackwell Science.
- Bullock TH and Horridge GA (1965) *Structure and Function in the Nervous Systems of Invertebrates*. San Francisco: Freeman.
- Burrows M (1996) *The Neurobiology of an Insect Brain*. Oxford: Oxford University Press.
- Gilbert SF and Raunio AM (1997) *Embryology. Constructing the Organism*. Sunderland, MA: Sinauer.
- Lacalli TC (2001) New perspectives on the evolution of protochordate sensory and locomotory systems, and the origin of brains and heads. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences* **356** (1414): 1565–1572.
- Mackie GO (1999) Nerve nets. In: Adelman G and Smith BH (eds) *Encyclopedia of Neuroscience*, pp. 1299–1302. Amsterdam: Elsevier.
- Maddison DR and Schulz K-S (eds) (2002) *The Tree of Life*. <http://tolweb.org/tree/phylogeny.html> [An excellent gateway to information on most animals.]
- Ruppert EE and Barnes RD (1994) *Invertebrate Zoology*, 6th edn. Fort Worth: Saunders College.