Mind the gap

How nerve cells communicate

Helena Bailes

Neuroscientist Helena Bailes explains how our nervous system solves the problem of transmitting electrical signals from one nerve cell to the next, and how this helps our brains to process information

Key words

Neurone
Synapse
Action potential
Neurotransmitter

Nerves send and receive information in the form of electrical impulses. This information might be instructions telling muscles to move, or messages from sense organs such as the eye to tell the brain what's happening in the world outside.

Our **central nervous system** consists of a network of billions of **neurones**. Extended strands on each neurone — **dendrites** — receive information and another strand — the **axon** — passes it on (see Figure 1). Within a neurone, information is encoded in the form of nerve impulses, called **action potentials** (see Box 1).

Action potentials are an ideal medium for very fast signal transmission with no loss of information. This is because they are 'all-or-none' signals — they are regenerated afresh at every point along the axon, so none of the signal is lost. And they can travel at speeds of up to 100 metres per second. However, a problem arises when an action potential reaches the end of the line — that is, the terminal of the axon (see Figure 1). Here it must be transmitted from one neurone to others in the network.

Action potentials cannot 'jump' from one neurone to the next. This is because the nerve cell membrane, which consists of a lipid bilayer, is an extremely good electrical insulator, restricting the passage of electrical current. In contrast, extracellular fluid conducts electrical signals well because it contains charged ions. An electrical signal that arrives at the axon terminal is quickly 'lost' in the extracellular fluid and cannot cross the gap to the next neurone in the network, even if the gap is very small. The nervous system has a way of overcoming this problem — it uses synapses.

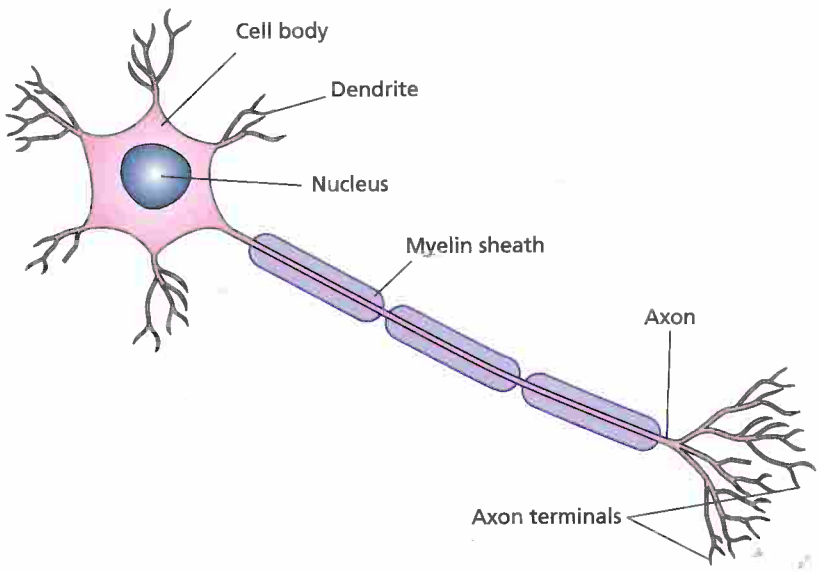

Figure 1 A typical neurone. Dendrites receive information from other neurones. Action potentials travel down the axon to the terminals. The myelin sheath is made of fat and helps to insulate signals travelling down the axon

Terms explained

Action potential A nerve impulse — an all-or-none electrical signal carried by an axon.

Axon The main process of a neurone that transmits action potentials.

Central nervous system The brain and spinal cord, containing nerve cell bodies.

Dendrite A branching process of a neurone that receives incoming signals from synapses.

Neurone A nerve cell.

Summation The process of adding together synaptic inputs arriving on a neurone.

Synaptic cleft The small extracellular space between neurones.

Threshold The point at which the potential difference between the outside and inside of a cell allows an action potential to fire.

Voltage-gated Ca^{2+} channels Channels in the membrane that open in response to a change in voltage to allow calcium ions to pass through.

Electrical synapses: the key to quick thinking

Some axons come into close contact with the dendrites of other neurones, with a gap between them of less than 5 nanometres. The two neurones overcome the problem posed by insulating lipid membranes by forming 'holes' through both membranes to link the cells together. Specialised structures between the neurones create tiny pores that provide direct contact between the cytoplasm of the two cells (see Figure 2).

Charged ions in the cytoplasm, such as Na^+, Cl^- and K^+, can move directly from one neurone to the next, carrying the electrical current required to transmit an action potential. In effect, the barrier between the two neurones is removed and action potentials are transmitted directly between them.

These specialised junctions between neurones are called electrical synapses. They transmit action potentials extremely quickly, with almost no delay between the two neurones. Animals have electrical synapses in nervous pathways that control very fast responses, such as those used to escape from predators. This has been well studied in crayfish, in which neurones connected by electrical synapses are responsible for initiating a fast tail flick that propels them away from predators and helps them avoid becoming a meal (see Figure 3).

Box 1 How moving ions cause action potentials

The concentrations of charged ions such as sodium (Na^+) and potassium (K^+) differ between the inside and outside of a neurone. This results in an electrical charge, or voltage, across the membrane — called the membrane potential. At rest the inside of the neurone is around 70 millivolts (mV) more negative than the outside, so we say that it has a membrane potential of −70 mV (see Figure 1.1).

Ion channels in the membrane can open and close, allowing specific ions to move into and out of the cell, thus altering the membrane potential. When the membrane becomes more positive (i.e. less negative) inside, special voltage-gated Na^+ channels open. Na^+ ions move into the cell, making it even less negative inside. When the membrane potential reaches a threshold of around −55 mV, an action potential is triggered. This is due to a positive feedback loop whereby inward movement of Na^+ ions causes even more Na^+ channels to open.

During an action potential the membrane potential of the neurone changes from −70 mV to around +40 mV — an overall change of 110 mV — in less than a millisecond. The action potential comes to a swift end when the Na^+ channels close and K^+ channels open. K^+ ions leave the cell, restoring the negative charge inside.

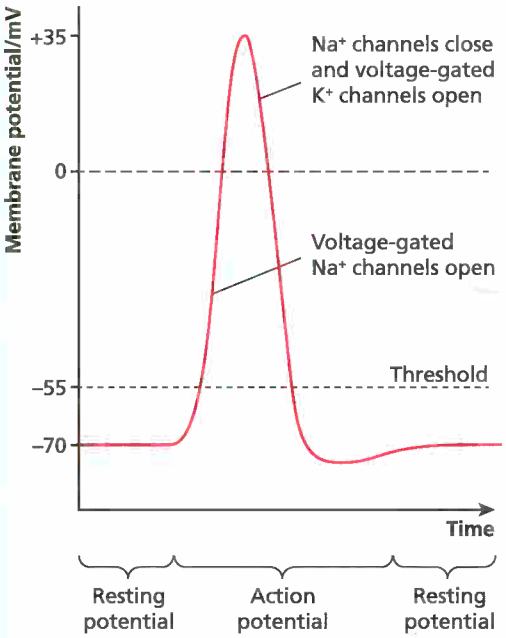

Figure 1.1

Jumping the gap using brain chemistry

Electrical synapses clearly do a good job. But in most cases the gap between neurones is too big — around 20–50 nanometres — so a different mechanism is needed here. This is the chemical synapse, where the action potential is converted into a chemical signal at the axon terminal of the first neurone and then back into an electrical signal in the second neurone. These chemical signals are called neurotransmitters.

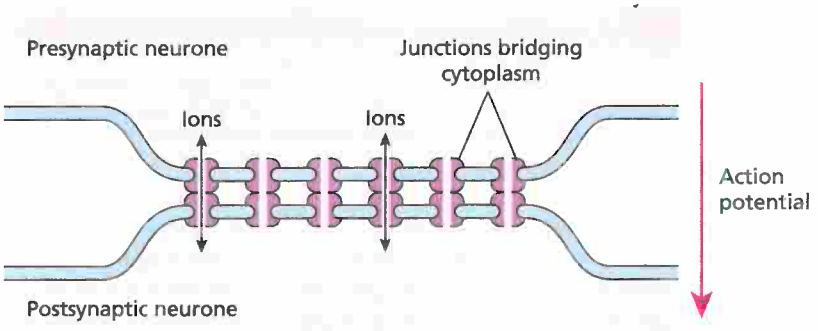

Figure 2 Structure of an electrical synapse between two neurones. The neurones come very close together. Specialised junctions span their membranes to connect the cytoplasm of the two cells. This means ions can move between the two. Charged ions flow through the junctions during an action potential

Figure 3 Many animals, such as this crayfish, use electrical synapses in pathways that must transmit signals extremely fast — for example, to escape from predators

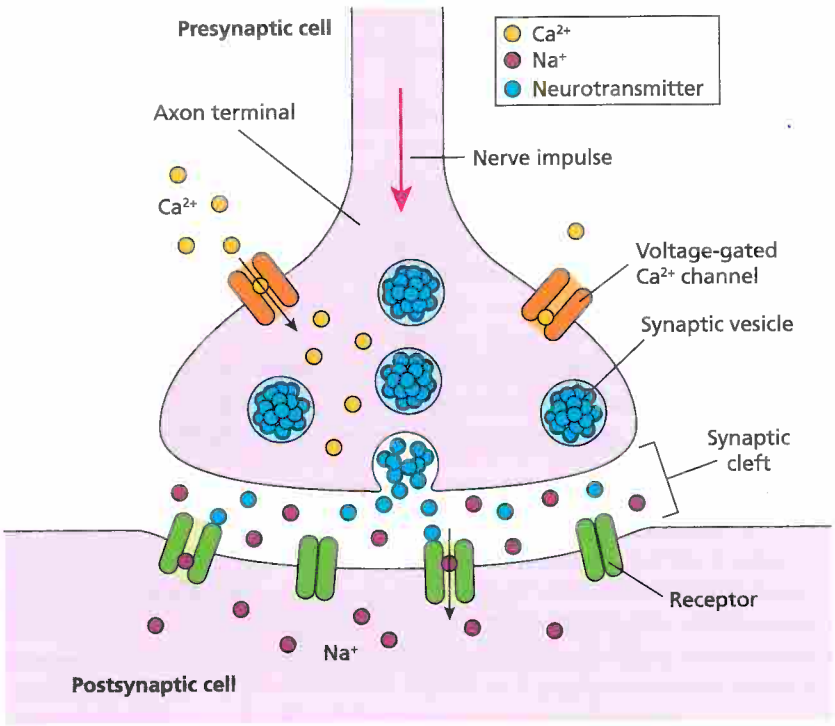

Figure 4 A chemical synapse converts an action potential into a chemical signal — neurotransmitter. The action potential opens voltage-gated Ca^{2+} channels. Ca^{2+} ions enter the axon terminal, causing vesicles containing neurotransmitter to empty into the synaptic cleft. Neurotransmitter is detected by receptors on the next cell, which open to allow ions into the postsynaptic cell. In this case the ion is sodium, a positively charged ion

When the action potential arrives at the axon terminal, the change in voltage across the membrane — the membrane potential — opens **voltage-gated Ca^{2+} channels** in the membrane (see Figure 4). Ca^{2+} ions enter the terminal from the extracellular fluid. The inside of the terminal is packed with vesicles containing a neurotransmitter chemical. The Ca^{2+} ions trigger the vesicles to fuse with the terminal membrane and release their neurotransmitter content into the gap — called the **synaptic cleft**.

There are more than 100 different substances that are used as neurotransmitters. Probably the best known is acetylcholine, which is released by neurones onto muscle cells to trigger an action potential and hence muscle contraction.

Once the synaptic cleft is flooded with neurotransmitter, the membrane of the second (postsynaptic) neurone detects it and generates a new electrical signal in order to keep the information flowing. This membrane contains receptors that recognise neurotransmitter molecules. The molecules bind to the receptors like a key in a lock to activate them.

Many of these receptors are themselves ion channels that, once activated, allow the movement of charged ions. If positive ions such as Na^+ enter the cell through these channels, the inside becomes more positively charged. This change in the membrane potential may be sufficient to reach the **threshold** to trigger an action potential and the message is passed on. This type of chemical synapse is called excitatory.

At other synapses the receptors activate ion channels that allow the passage of different ions. If the ion channels are selective for Cl^- ions, these ions

Further reading

An excellent overview of synapses:
www.biologymad.com/nervoussystem/synapses.htm

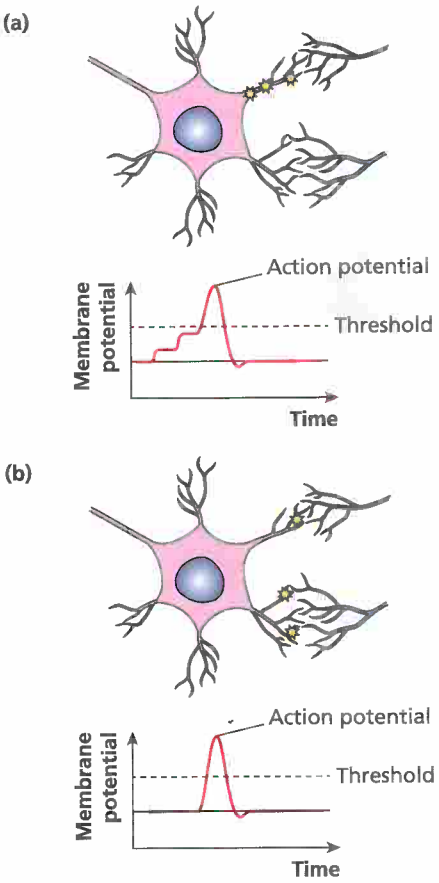

Figure 5 The timing and location of signals arriving from different synapses is summed by the cell body. In **(a)** a single synapse signals three times in quick succession. The changes in membrane potential in the postsynaptic cell add together (see graph of changes in membrane potential, or voltage, during this period). The membrane potential reaches threshold and the neurone fires an action potential. In **(b)** three different input synapses fire simultaneously. The electrical responses again sum, causing the membrane potential to reach threshold and fire an action potential

enter and make the neurone more negative inside. The membrane potential moves further away from the threshold for an action potential. In this case the signal is not passed on. These synapses are called inhibitory.

It all adds up

While Figure 4 shows one neurone synapsing onto one other neurone, in reality neurones can receive information from hundreds or even thousands of others via synapses. How is all this information processed to ensure that important signals get through and are not lost amid the huge mass of inputs?

A neurone has to make split-second decisions about whether or not to fire an action potential, based on all of the inputs coming in — some excitatory and some inhibitory. It is the job of the neurone's cell body to add together all these signals

Your brain filters out the unwanted sounds so that you can concentrate on your conversation

at any given moment, and then 'decide' whether to fire (see Figure 5). The adding up process is called **summation**.

If the final summed electrical signal is large enough — and so exceeds threshold — an action potential will be generated. If an excitatory and an inhibitory synaptic input arrive on a neurone simultaneously, they are likely to cancel each other out. It is probable that vast amounts of information in your brain are filtered out in this way.

Imagine you are at a party, listening to a friend talk. Your brain will filter out the sensory signals triggered by the music and noise of others talking to enable you to concentrate on your friend. This is called the 'cocktail party effect' and illustrates how your brain can decide which signals to pay attention to, and which to ignore. And all this happens without you even being aware of it.

What we can learn from chemical synapses

Because of the time taken for neurotransmitters to be released, bind to receptors and trigger a new action potential, chemical synapses delay signal transmission by about 1 millisecond. This may not seem much but it can add up, especially when a pathway involves many neurones and synapses. And, when escaping a predator, the speed of signal transmission can be a matter of life and death.

Chemical synapses do, however, have their advantages. They show a phenomenon called synaptic plasticity, in which the strength of an individual synapse can change. This is achieved by changes in both the amount of neurotransmitter released per action potential, and the number of receptors available to bind neurotransmitter — changes that are not possible for electrical synapses. A change in synaptic strength alters the likelihood of a signal getting through to the next stage in the pathway. Scientists have shown that synaptic plasticity underlies learning and memory in animals as diverse as worms, slugs, flies and mammals such as ourselves.

Neuroscience is an ever-growing field exploring the hidden world of nerve cell communication in our heads. The combination of electrical and chemical synapses, together with a vast range of neurotransmitters and many different types of receptor, is the key to the brain achieving such complexity in the way it processes information.

Things to do

- How fast can signals travel along neurones and across synapses to cause a response? Test your reactions here:
  www.bbc.co.uk/science/humanbody/sleep/sheep/reaction_version5.swf
  http://tinyurl.com/pn6mwps

Dr Helena Bailes teaches neuroscience and biomedical sciences in the Faculty of Life Sciences at The University of Manchester. She also researches the different mechanisms used by the light-sensing molecules responsible for vision across the animal kingdom.

Key points

- Signals travel along neurones as a wave of electrical charge called an action potential.
- Electrical signals cannot 'jump' between neurones.
- There are two types of connection between neurones: electrical and chemical synapses.
- The neurone's cell body sums synaptic inputs together to 'decide' whether to fire.
- Chemical synapses can change their strength — a process called synaptic plasticity.